ANALYSIS OF CHARGING AND DRIVING BEHAVIOR OF PLUGIN ELECTRIC VEHICLES THROUGH TELEMATICS CONTROLLER DATA

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

1.	BEV	Battery Electric Vehicle
2.	CSOC	Current State of Charge
3.	EREV	Extended Range Electric Vehicle
4.	EV	Electric Vehicle
5.	EVSE	Electric Vehicle Supply Equipment
6.	FTP	File Transfer Protocol
7.	HEV	Hybrid Electric Vehicle
8.	ICE	Internal Combustion Engine
9.	kWh	kilowatt-hour
10.	MPG	Miles Per Gallon
11.	MPGe	Miles Per Gallon Equivalent
12.	PEV	Plugin Electric Vehicle
13.	PHEV	Plugin Hybrid Electric Vehicle
14.	SAE	Society of Automotive Engineers
15.	TCU	Telematics Control Unit
16.	TOU	Time of Use
17.	VPN	Virtual Private Network

SUMMARY

Very little information is known about the impact electrification has on driving behavior, or how drivers charge their electrified vehicles. The recent influx of electrified vehicles presents a new market of vehicles which allow drivers the option between electrical or conventional gasoline energy sources. The current battery capacity in full battery electric vehicles requires planning of routes not required of conventional vehicles, due to the limited range, extended charging times, and limited charging infrastructure. There is currently little information on how drivers react to these limitations.

A fleet of fully electric and plug-in hybrid electric vehicles transmitted data wirelessly, which is then analyzed. The data includes battery state of charge, distance of miles driven on gasoline and electric, energy consumed, and many other parameters associated to driving and charging behavior. In this thesis, this data was processed and analyzed to benchmark the performance and characteristics of driving and charging patterns. Vehicles were analyzed and contrasted based on model type, geographic location, and other variables.

This data was able to show benchmarks and parameters in aggregate for over a year of electrified driving. These parameters were compared to the EV Project, a large scale electrified vehicle study performed by Idaho National Labs, to confirm patterns of expected behavior. This study provides benchmarks and conclusions on new driving behavior. Analysis of the differences on charging and driving behavior between geographic regions and experience were examined, providing insight to how these variables affect performance and driving and charging patterns. Comparison of parameters established by the EV Project and new parameters analyzed in this report will help build a benchmark for future studies of electrified vehicles.

CHAPTER 1

INTRODUCTION

1.1 Background

Electrified vehicles have been taking up larger market share of retail vehicles in the United States in recent years. Particularly with plugin electric vehicles (PEVs) which allow the driver to plug in their vehicle and drive with all or a portion of their trip using electricity from an on board battery. These can include battery electric vehicles (BEVs), which use no gasoline and rely solely on a battery to propel the vehicle, and plugin hybrid electric vehicles (PHEVs), which have a limited electric range and a smaller battery combined with a conventional gasoline engine. Extended range electric vehicles (EREVs) are another type of PEV which only utilizes an electric motor to propel the vehicle, but contains an onboard gasoline generator to extend the range of the battery. This differs from a PHEV in that the gasoline generator cannot apply additional power to the wheels, but only supplement the battery range. With PEV sales rising into the tens of thousands per year, new charging infrastructure will likely be installed to support these vehicles. Government institutions benefit from understanding how these vehicles are being charged and driven, in order to optimize charging infrastructure deployment to best serve customers in their local municipalities. Vehicle manufacturers and research institutions are also eager to understand how vehicles are used in order to optimize future PEV designs and improve range, performance, and efficiency.

Little information is known about how these new electrified vehicles are being driven or charged. Conventional internal combustion engine (ICE) vehicles are restricted to a single fuel source, traditionally either gasoline or diesel fuel, both of which being petroleum based. These types of vehicles have been the standard for decades and robust infrastructure has been developed to accommodate them. An owner of a conventional ICE vehicle has very little concern about refueling, as it is a standard process that takes very little time, and gas stations are ubiquitous enough that finding one is generally a non-issue.

Full battery electric vehicles however have a drivable range that is a fraction to that of a conventional vehicle, due to the limits of present battery technology; and recharging the vehicle requires a dedicated charge station and several hours to fully recharge. Without dedicated equipment in place a BEV can take up to 20 hours to recharge fully from a standard 120 volt outlet. This requires careful planning, which must be done daily, of what trips are to be taken with the BEV and when it will be available to be recharged. A BEV owner cannot use the same driving and refueling behavior as a conventional vehicle, as the recharging time is much longer than the time required to refuel, and the smaller vehicle range requires recharging more frequently than would be necessary for refueling. These adjustments in driving behavior are made on an individual basis for what matches the driver's specific situation. This paper will investigate what changes in driving and charging behavior these customers have made, and how it differs from conventional vehicle operation.

Plug-in hybrid electric vehicles (PHEVs) are vehicles which can drive in full electric mode using a battery pack similar to a BEV, but with the addition of a gasoline engine, which can supply power in conjunction with the electric motor, or on its own if the electric battery's charge is depleted. PHEVs generally have a smaller battery capacity than a BEV and therefore a shorter range available to them for all electric driving. A

PHEV driver can potentially drive the vehicle without altering their behavior from that of a conventional vehicle, as it can operate on gasoline, however this paper will focus on the particular differences in how these drivers operate from both BEVs and conventional gasoline vehicles.

This paper seeks to identify PEV driving and charging behavioral patterns as well as statistics on performance of these vehicles. Benchmarks established from other studies will be compared to the participants of this study, in order to confirm or contrast between resulting behaviors. In areas of electrified vehicle performance which have not previously been investigated on a large scale, this paper seeks to establish these metrics as the baseline for future investigations. In general this work strives to present all information and insights to electrified vehicle driving and charging behavior derived from the data which could establish understanding for future work.

1.2 Project Overview

This project analyzed data acquired from a fleet of electrified vehicles both from industry sources as well as public sources. Each PHEV and BEV sends data in packets using the telematics control unit (TCU) which are then analyzed off board.

Each message packet has specific data parameters which are included with the message. These contain information about the state of the vehicle, a summary of the trip specifics, such as distance traveled using electricity and distance traveled using gasoline. Charge information such as when the vehicle is being charged and for what duration is also included in various message packets.

1.3 Electrical Infrastructure

The PEVs analyzed in this report utilize a SAE J1772 standard plug for charging, which allows for level 1 and level 2 AC charging (SAE 2012). Level 1 charging is done at 120 V and can be utilized from a standard electrical outlet in North America. This type of charging is satisfactory for time spent away from a dedicated charging station, but requires more time to complete a charge than level 2 charging. Level 2 charging is performed at 240 V in North America and requires dedicated electrical vehicle supply equipment (EVSE). EVSEs can be built for both level 1 and level 2 charging, but are typically manufactured for only level 2 charging.

Many new PEVs are allowing the option for level 3 DC charging, which can recharge a vehicle to 80% state of charge in less than an hour. These fast charge EVSEs are typically found in urban areas or connecting points between cities, which would allow for fully electrified driving between cities. There are currently two popular standards for level 3 DC fast charging, the SAE DC Combo plug, which is an adaptation of the J1772 plug, and the CHAdeMO connector.

1.4 Organization

This paper will begin with an investigation of the previous studies performed on electrified vehicles, and discuss the results they've found while taking into account the size of their fleets and any discrepancies in technology used. The major study this paper seeks to draw comparisons with will be the EV Project conducted by Idaho National Labs and ECOtality from 2011 to 2013. The EV Project is the largest study to date to be conducted on the behavior of both BEVs and PHEVs.

After a background of previous data has been investigated the methodology of this study will be presented. This section will be dedicated to analyzing what collection techniques were utilized in both the industry vehicles and EV Project vehicles.

The next chapter will lead in to the basic metrics which were analyzed in this project. All parameters which were analyzed will be explained and the logic and equations which derived them will be produced. Results of these metrics will be analyzed and presented, revealing different behaviors that were observed for the various parameters examined.

Once the initial results and parameters have been fully explained this paper will seek to validate these results and compare metrics to the original EV Project, which shares many of the analyses that will be conducted here.

Next the parameters which are particularly unique to this study will be examined. These results are newly presented from a large fleet of electrified vehicles and will be the first look at how these vehicles are performing to these parameters. This section will hope to establish credibility in the results derived and hopes to serve as a benchmark for future studies to analyze similar behaviors.

Lastly a conclusion of results and future work needed on electrified vehicle fleets will be established. This is a new topic for investigation and as electrified vehicles become more prevalent there will be a need for greater understanding in how they are being utilized. This greater understanding has the potential to lead to more efficient infrastructure development and data driven vehicle design.

CHAPTER 2

LITERATURE REVIEW

This literature review seeks to summarize the information that has been collected on driving and charging behavior for both BEVs and PHEVs and identify what aspects have yet to be fully explained or verified. The greatest source of information, and most comparable study comes from the EV Project by Idaho National Labs and ECOtality. The EV Project study began in 2011 and looked into the driving and charging behavior of several thousand PEVs, with a particular interest in charging infrastructure. The EV Project was able to capture a broad range of data on vehicle driving and charging behavior and will be reviewed extensively in this section. First however, a look at some less significant studies which laid the ground work for this one.

2.1 Minor Telematics Studies

2.1.1 G-VAN Data Acquisition and Analysis – The Empire State Electric Energy Research Corp.

The Empire State Electric Energy Research Corporation (ESEERCO) sponsored a project in 1994 in which 15 G-Vans (fully electric GMC work vans) were in service to three New York State utilities (Colasanti, Landsberg et al. 1994). Their performance was logged on board at the end of each trip and transmitted via cellular network to a database where it was analyzed. Over a year and a half the project logged over 57,000 miles and achieved efficiencies on average of 1.45 kWh per mile. The study concluded that the vehicle performance was most affected by the operating environment between rural and urban areas.

2.1.2 Technology Acceleration and Deployment Activity – Idaho National Labs

In 2009, data collection began for a project which included 21 Ford Escape PHEVs, operated by various fleets throughout the world (Carlson, Shirk et al. 2012). Data was collected over a 3 year period which logged a total of over 500,000 miles of driving. Both trip and charging data was collected in order to investigate factors which impacted electric driving and fuel efficiency. The study concluded that increased public infrastructure for frequent charging, a mild ambient operating temperature, and short to mid-range trips were the factors which most impacted efficient driving for the PHEV fleet.

2.1.3 Versatile Data Acquisition System

In 1985 three battery electric vehicles were retrofitted in Virginia and California with a microprocessor to capture battery performance information from the vehicle while in use (Kevala and Kwan 1985). The trip information was then processed to understand the energy consumption per mile and power and energy demands. They also investigated the battery charge profile and component temperature extremes during operation. They concluded that collecting data through the versatile data acquisition system could provide a bridge to the gap between simulations and field tests for electric vehicles.

2.1.4 Chrysler Ram PHEV Pickup Trucks

In May 2011 Chrysler launched a 3 year demonstration program in which 140 Ram 1500 PHEV pickup trucks are put through a testing regimen with the goal of achieving 6 million miles of real world driving (Buchholz 2011). The trucks were converted to a PHEV with a 20 mile range and a 12.1 kWh lithium ion battery. The project is co funded by the Department of Energy with hopes to gain data on the usage and performance of these pickup trucks.

2.2 The EV Project

Much of the current information on PEV charging and driving behavior comes from the Idaho National Labs EV Project. The EV Project is a large scale infrastructure study which includes 8,300 PEVs at peak enrollment, which began in the winter of 2010 (Stephen, John et al. 2012). The study includes both the Nissan Leaf BEV and the Chevy Volt EREV. There are also 14,000 level 2 EVSEs installed at peak from ECOtality's Blink network. This study is a partnership between ECOtality, Idaho National Labs, General Motors, Nissan Motor Company, and the Department of Energy among other partners. It is the largest study to date, collecting data from both the vehicles and the networked charging stations. This combination of data collection allows understanding of how vehicles are being driven as well as detailed information on when and how they are charging.

2.2.1 Charging Behavior

The charging behavior of PHEVs and BEVs varies, due to the difference in average battery sizes, as well as different charging needs of the customer. BEVs inherently require charging in order to operate as they have no other fuel options, whereas PHEVs have the liberty to charge when convenient. In the EV Project (John and Stephen 2012) it has been observed that 82% of charging occurred at the vehicle owner's home, with 18% charging elsewhere, either in public or at work. Recent data shows that BEVs on average charge away from home 20% of the time while PHEVs charge 14% of the time outside of the home (ECOtality 2013) . Of these, 70% of vehicles had charged outside of the home at least once while owning the vehicle. When charging away from home the state of charge (SOC) of the battery is higher than when charging at home, and the end SOC is less likely to reach a full 100%, which supports the idea that charges away from home are supplemental. When participants do charge their vehicles away from home, the ideal locations are those in which the participant's vehicle will be parked for one to three hours (ECOtality 2013). It was found that the type of venue was less of a factor than perhaps specific location, as similar venue types varied widely in EVSE utilization. On average BEVs charge less often than PHEVs at 1.1 charge events per day to 1.5 charge events per day respectively (ECOtality 2013). These additional charge events occur more often at home than elsewhere.

The EV Project has found that owners will adjust their time of charge based on utility time of use (TOU) rates, if they offer enough financial incentive (ECOtality 2013). This varies based on the market and the specific rates of the utility, but for those that offer strong incentives 57% of PEV owners change their utility rate plan in result of purchasing a plug-in electric vehicle. Owners will program their vehicles or their EVSE in order to take advantage of TOU rates, a small fraction of owners will program both. The EV Project found that of those who have scheduled a charge within the past 6 months, 38% respondents program their vehicle, 25% program the EVSE, and 11% will program both (ECOtality 2013). However when taking into account all participants in the project the number of people who schedule their charging varies from market to market, with 62% of respondents in San Diego programming their charge events and only 8% in Philadelphia doing the same. Average charge programming was between 15 and 30 percent.

DC Fast Chargers (DCFC) allow BEVs to recharge from 30% to 80% SOC in approximately 25 minutes, and are slowly becoming more available in areas of the country to extend the range of BEVs. The EV project has found that BEVs utilize DCFC mostly during peak hours (9 am to 10 pm) and that each DCFC station averages 16 charge events per week (ECOtality 2013).

2.2.2 Driving Behavior

PHEV and BEV driving patterns vary most predictably due to the limitations in range. A BEV is restricted to the size of the battery whereas a PHEV can utilize the battery for short trips and rely on traditional gasoline fueling infrastructure to extend the range to hundreds of miles before requiring a simple refueling. DC Fast Charging Stations are slowly being integrated into the infrastructure, increasing the range of BEVs, but it still requires a break of approximately 30 minutes to charge. The EV Project has found that the average annual miles driven for PEVs is 9000 miles, with PHEV drivers driving 39% farther each day than BEV drivers (ECOtality 2013) . The average PHEV drives 41.0 miles per day, while the average BEV drives 29.5 miles per day, however the distance between charge events is roughly the same, with 27.6 miles for PHEVs and 26.7 miles for BEVs.

Average trip length for BEVs in the EV Project is 7.1 miles with 3.8 trips on average between charging events. PHEVs have an average trip length of 8.3 miles with an average of 3.3 trips between charge events.

Outside of the EV project others have investigated the driving patterns of drivers in electrified vehicles as well as conventional vehicles. There has been an interest in finding how many people could sensibly switch to an electrified vehicle while maintaining their current driving patterns. This has been done by tracking conventional gasoline vehicles through GPS, and then determining how often this range would exceed the BEV's electric range. A study in Seattle found that a BEV with a 100 mile range would satisfy the driving for 50% of one vehicle households, and 80% of multi-vehicle households, with a driver needing to adjust their driving schedule or utilize another vehicle only four days out of the year on average (Khan and Kockelman 2012). Drivers will occasionally underestimate their driving needs, which could lead to range anxiety in a BEV (Hahnel, Gölz et al. 2013). Commercial fleets have also been found to alter their driving behavior in order to maximize electric usage (Wikström, Hansson et al. 2014). Commercial fleet owners and managers have also experienced increased interest in integrating electrified vehicles in to their fleet after trial experiences with electrified vehicles.

The current driving patterns of a driver are an important factor in the purchasing decision of an electrified vehicle, with BEVs having a much more likelihood of being purchased as a second vehicle (Neubauer, Brooker et al. 2012). The role of a vehicle, functioning as either the primary or secondary vehicle in a household, will greatly differentiate its driving patterns. For this reason PHEVs differ in driving patterns from BEVs, in addition to the obvious restrictions of range on the BEV. Additionally the battery sizes of various PHEVs can be found to be best suited for different driving styles and functions, as one battery size may not be able to fulfill the needs of all drivers (Redelbach, Özdemir et al. 2014).

2.3 Range Anxiety

One of the key metrics being investigated in this study is range anxiety, which is the fear of running out of electrical charge before reaching your destination, something a BEV driver may experience. Range anxiety is seen as a specific type of anxiety similar to what could be experienced by a gasoline driver running with very low fuel where the next gasoline station is an unknown distance away (Nilsson 2011). This experience has been investigated since the early 90’s when electric vehicles first started coming to market as experimental or leased vehicles. At this point it was noted that drivers wanted a vehicle with range similar to a gas vehicle, despite their actual driving needs (Kurani, Turrentine et al. 1994). The problem of finding what amount of range is actually necessary for an electric vehicle has been estimated by tracking gasoline drivers, to discover the range requirements if the driver were to switch to an electric vehicle. (Pearre, Kempton et al. 2011). One particular study collected driving data from 484 gasoline drivers for a full year and assumed that if they had an electric vehicle they would charge every night at their home. They found that 9% of drivers never travelled further than 100 miles in one day and 21% never exceeded 150 miles. If a driver was willing to alter their driving habits (perhaps by charging their vehicle during the day or borrow a gasoline vehicle) up to six times per year, then the 100 mile range would satisfy the driving of 32% of all drivers. This indicates that with minimal driver inconvenience or driving adaptations a significant segment of the population could potentially utilize electric vehicles. However the range of most electric vehicles today does not reach 100 miles without conscious effort made to reduce fuel consumption during driving.

Despite the ability of electric vehicles to cover the majority of driving, users still desire a considerably higher range, closer to that of a gasoline vehicle (Dimitropoulos, Rietveld et al. 2013). It has been found that when drivers are given time with an electric vehicle their range desires equate more closely with their needs (Graham-Rowe, Gardner et al. 2012). If a driver has experience with electric vehicles and drives one every day it has been found that they will feel more comfortable with the range they have available (Franke and Krems 2013). Drivers in general have been found to have a more positive view of electrified vehicles after driving them, with increases in positive perceptions of 78.6% in commercial fleet users over an extended period of time (Wikström, Hansson et al. 2014). However they still enjoy a range buffer of about 20-25% on average, though it differs considerably between individuals. A range buffer is the amount of range needed to be leftover before pursuing a trip, for example, a range buffer of 25% would require that a 40 mile trip have a 50 mile range available before initiating the trip. It was also found that the personality of the individual is an important factor to how they will experience range anxiety, as those who are more impulsive will suffer more from range anxiety. In addition, how users interact with other charge limited devices such as cell phones can influence how they will interact with electric vehicles (Franke and Krems 2013).

There have been many proposed solutions to range anxiety, though it has not been understood how these reduce range anxiety nor to what effect (Nilsson 2011). Potential strategies to alleviate range anxiety include informing the driver of the current state of charge, reducing the fuel consumption of the vehicle to prolong the charge, increasing available charging opportunities, or providing backup solutions such as a gasoline generator. Some research has found that range anxiety can be reduced by an increase in charging infrastructure (Neubauer and Wood 2014). Having a dedicated EVSE at home to reduce charging time, having charging opportunities at the workplace, and having broadly available public charging, all showed reduction in range anxiety.

2.4 Environmental Benefits

Electrified vehicles have the potential to reduce the environmental impact of the transportation sector, which currently accounts for 28% of energy consumption and 33% of carbon dioxide emissions in the United States (Kelly, MacDonald et al. 2012). Liquid fossil fuels currently account for 96% of the current energy supply to the global transportation sector (Forum 2011). Commercial fleets in Sweden have found reductions in energy consumption from 162.3 MWh to 60.5 MWh in 174 electrified vehicles over an 18 month period (Wikström, Hansson et al. 2014). This corresponds to a reduction in CO2 emissions from 45 tons to approximately 5 tons, as the energy consumption is switched from petrol to cleaner grid electricity. These results are obviously dependent on the electricity grid, and areas with more fossil fuel derived electricity will find less benefits, if any at all (Doucette and McCulloch 2011). There is a relationship between the amount of CO2 generated by the grid and which vehicle type is optimal for reducing environmental impact, and in areas with high emissions from grid electricity, a PHEV can have lower emissions overall than a pure BEV (Doucette and McCulloch 2011).

There is a particular benefit found in cold start scenarios where gasoline engines emit greater amounts of emissions in order to reach an efficient operating temperature. Electrified vehicles can reduce or eliminate this phenomenon compared to conventional vehicles (Zhang, Brown et al. 2011).

2.5 Electrified Vehicle Economics

All electrified vehicles require a capital investment over conventional vehicles in order to pay for the added electric propulsion components, such as batteries and electric motor. BEVs are expected to breakeven in price with hybrid electric vehicles (HEVs) by 2026, and conventional vehicles by 2032, based on cost reductions in electrical components and vehicles in general (Weiss, Patel et al. 2012). Several studies and surveys have been done on driver perceptions of electrified vehicles, both with drivers who have and do not have EV experience. When consumers were surveyed in San Diego, California it was found that the majority desired small range PHEVs compared to more expensive long range PHEVs and BEVs (Axsen and Kurani 2013). This corresponds to similar studies showing that the range is the most important factor for all electric vehicles and cost being second, followed by the desire to be environmentally friendly, which has a negligible impact on actual purchasing decisions (Egbue and Long 2012). Choosing a low range PHEV makes sense in this regard as it removes the aspects of range anxiety, due to the option to consume gasoline, while also minimizing cost, and it has been found to be more popular than full electric vehicles in purchasing decisions (Carley, Krause et al. 2013).

In the past few years there has been a noticeable change in the stereotypes associated with electric vehicles, as previously being considered “second class” vehicles, to more positive views as they become more mainstream (Burgess, King et al. 2013). But these positive trends still have not produced buyers to the levels estimated in market share predictions (Lieven, Mühlmeier et al. 2011). Predictions of 5% market share in Germany for example have been underperforming to a market share of 0.34% in 2013 for Western

Europe, which includes PHEVs and BEVs (Winton 2014). PEVs in the United States however achieved a market share of 0.58% (Klippenstein 2014).

CHAPTER 3

METHODOLOGY

The primary goal of this thesis is to acquire an understanding of how individuals are driving and charging their electrified vehicles, and how this behavior differs from conventional vehicles. A traditional problem in this field has been having a large enough data set to understand the behavior of electrified fleets while limiting the potential impact localized fleets will have on the data, such as constraining oneself to a single geographic region, or to vehicles fulfilling a specific function such as mail carriers. However in this study data has been collected from a large fleet of vehicles from across North America, who use these vehicles for both personal and business use. A challenge in this study is to draw analytical conclusions from such a large data set and discover what variables most affect the performance of charging and driving behavior. This study hopes to leverage such a large data set to better understand how electrified fleets are utilized in a wide range of applications and environments.

3.1 Data Collection

A driver will opt in to the program and data will begin being collected from their vehicle automatically. Data is collected into message packets by the telematics control unit (TCU) and then delivered to a data server. These message packets are organized into trip and charge information, with each message having parameters attached which indicate the status of the vehicle. These parameters include the state of charge as well distance travelled on gasoline and electricity on the last trip.

3.2 Data Processing

After this is done all of the relevant information associated to trip and charge events is assembled and organized chronologically. This information is then written to separate trip and charge files. These files are split in various ways by model type or geographic area for example. Below is a list of the data found in the trip and charge files.

3.2.1 Trip File

CSOC – The current state of charge of the lithium ion battery at both the beginning of the trip and the end of the trip.

Timestamps – Timestamps at the beginning and end of the trip.

Odometer – Odometer reading at the end of the trip.

EMD – Electric miles driven during the trip, this is the distance driven with the gasoline engine off, only using the electric motor for propulsion.

Trip Length – Total length of the trip in miles.

Energy Consumed – The energy consumed in kWh during the trip as well as the total gallons of gasoline consumed.

DTE – The distance to empty in miles for the electrical battery to reach zero state of charge as well as for the gasoline fuel tank to be empty, at both trip start and end.

State – The US State in which the trip ended, if the trip ended in Canada the province is not available but a Canadian indicator is used.

Duration – The duration of the trip in minutes.

Avg. Speed – The average calculated speed of the trip in miles per hour, calculated using the following equation:

$$Avg\ Speed\ (mph) = \frac{Trip\ Length\ (mi)}{Trip\ Duration\ (min)} * 60 \tag{1}$$

3.2.2 Charge File

CSOC – The current state of charge at the beginning and end of the charge event.

Timestamps – Timestamps at the beginning and end of the charge event.

Odometer – Odometer reading of the vehicle during the charge event.

Charger Type – Indication of the EVSE type, level one, level two, or DC.

State – State in which the charge event occurred, if Canada no province is shown.

These trip and charge files contain all of the necessary information to analyze the behavior of the industry fleet. In step two of processing, the trip and charge files are processed on a per week basis. The code analyzes information in aggregate to generate weekly values to form a summary over time. The analysis performed on the organized data of the trip and charge files will be discussed in depth in the next chapter.

CHAPTER 4

ANALYTICS

Once all of the data has been neatly organized by week in the trip and charge files, analysis on driving and charging behavior can begin. There are many metrics which were analyzed during this study, many of which correspond with the EV Project performed by Idaho National Labs, and others which have not been analyzed on this scale. The metrics which are most defining to the study will be presented in this chapter, while the remaining metrics will be found in the appendix.

4.1.1 Average Trip Length

An important parameter to be analyzed is the average trip length taken by the vehicles. This can help indicate the sizing of the battery necessary for future electrified vehicles, as well as understanding what percentage of driving can be done with current vehicle choices. The average trip length can be found in Figure 1 below.

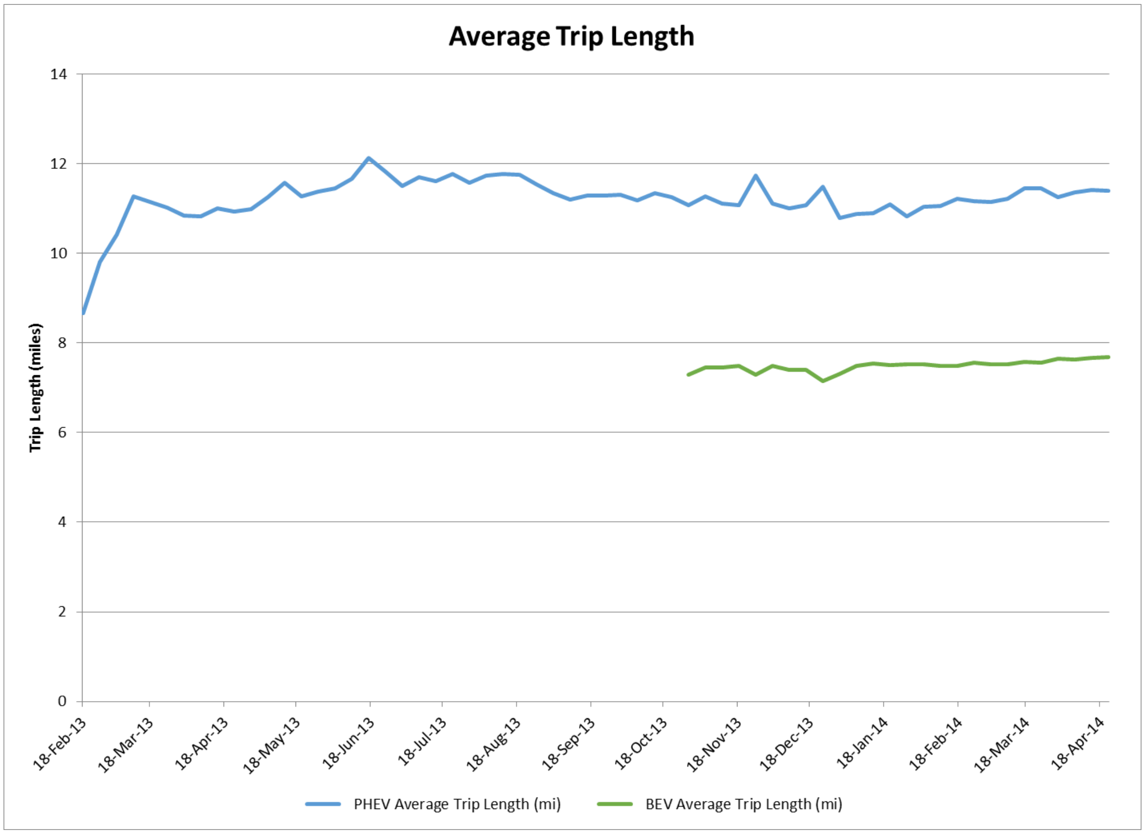

Figure 1 Average Trip Length in miles for both PHEVs and BEVs

The PHEVs have an average trip length that holds fairly consistently around 11 miles, with a rise during the summer months, which is due to the very long trips which are more frequently taken during the summer, raising the average. The PHEV is capable of taking trips several hundred miles long, which inevitably raises the average. This reduces the average in comparison to PHEVs because BEVs are not capable of taking very long trips.

4.2 Charge Analytics

4.2.1 Charge Events per Week

There are many metrics that indicate how the vehicles are charging, and how their behavior differs under varying circumstances. One of the primary goals of this thesis is to identify how vehicles are charging and how their behavior differs over time, and between model types such as PHEVs and BEVs.

One of the primary metrics of charging behavior is the number of charge events performed per week by the vehicle owner. A charge event is classified as beginning when the vehicle begins to accept charge, from either a dedicated EVSE or a standard wall outlet; and it ends when either the vehicle has fully recharged or the user has unplugged the vehicle. The charge events per week can be seen in Figure 2 below.

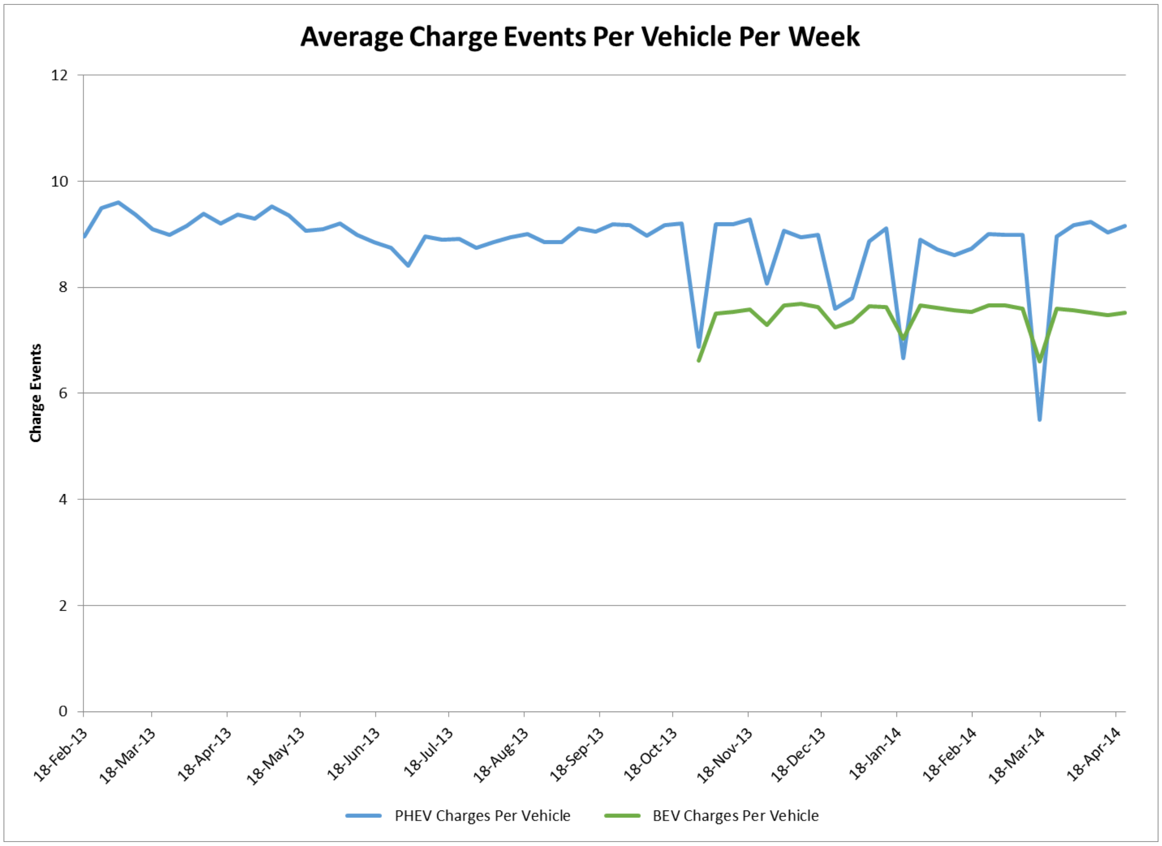

Figure 2 Average Charge Events per Week for PHEVs and BEVs

Here it can be seen that PHEVs on average charge between eight and ten times per week, where BEVs charge an average of six to eight times per week. There are noticeable drops in charge events during holiday weeks such as Thanksgiving in late November and

Christmas in December, when drivers are at home and generally do not need to charge their vehicles. The drops found in the first week of BEV data, the end of January 2014 and in the end of March 2014 are a result of incomplete data.

There are two driving forces to the reasons that PHEVs charge more often than BEVs. Firstly, the battery capacity of a BEV is much larger than a PHEV. For daily driving it is not necessary for the BEV to charge every day, and as range anxiety is diminished the owner may choose not to charge every day. Though initially, BEV owners will charge often to avoid the risk of running out of charge when needed (Caperello, Kurani et al. 2013). A PHEV owner however will charge more often to keep the smaller battery charged, in order to maximize electric driving.

This leads to the second reason, it could be argued that a PHEV owner does not need to charge as often because they have the gasoline engine with which to fall back on, so there is no range anxiety associated to driving, as seen in a BEV. However, it has been seen that PHEV owners will deliberately avoid using gasoline in their driving in order to maximize savings (Krupa, Rizzo et al. 2014). With the removal of range anxiety, it is not a change in behavior created out of necessity for fear of running out of charge but more as a game, to maximize their fuel economy. Electrified vehicles have careful recording of fuel use visible to the driver at a nearly constant level, and this awareness creates a need by the driver to minimize fuel consumption (Nilsson 2011). PHEV owners will alter their behavior not out of necessity, but out of desire to maximize fuel savings.

4.2.2 Trips and Distance between Charges

This leads to other useful metrics to analyze, such as how many trips do users take between charges, and how long are those trips before they decide to recharge. Below in Figure 3 is the average number of trips taken between charge events for PHEVs and BEVs.

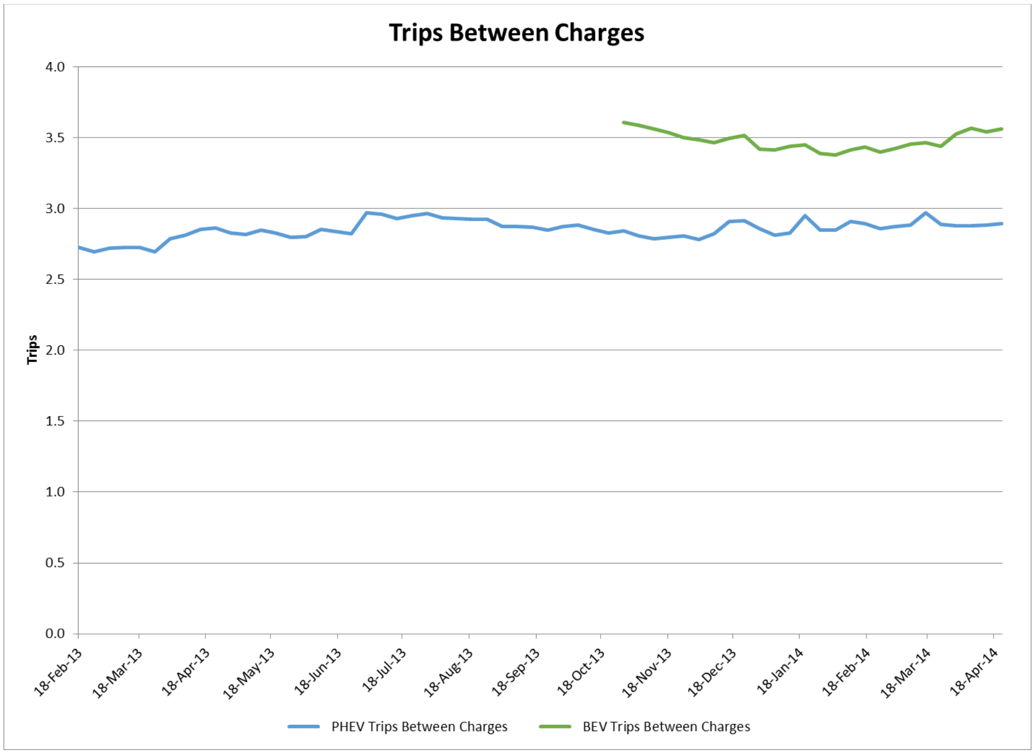

Figure 3 Trips taken between Charge Events for PHEVs and BEVs

On average PHEVs and BEVs take similar number of trips between charge events, PHEVs between 2.5-3.0 trips on average and BEVs around 3.5 trips between charge events . PHEVs travel on average between 30-35 miles between charge events. BEVs on the other hand travel between 25 miles on average between charge events. Though BEVs have considerably more range than 25 miles, they choose to charge sooner. This again can be attributed to range anxiety experienced by BEV owners. It can also be seen that there is a decline in the distance traveled between charge events during the winter months, when colder temperatures reduce the performance of the battery, requiring charging for a shorter distance traveled on electricity alone.

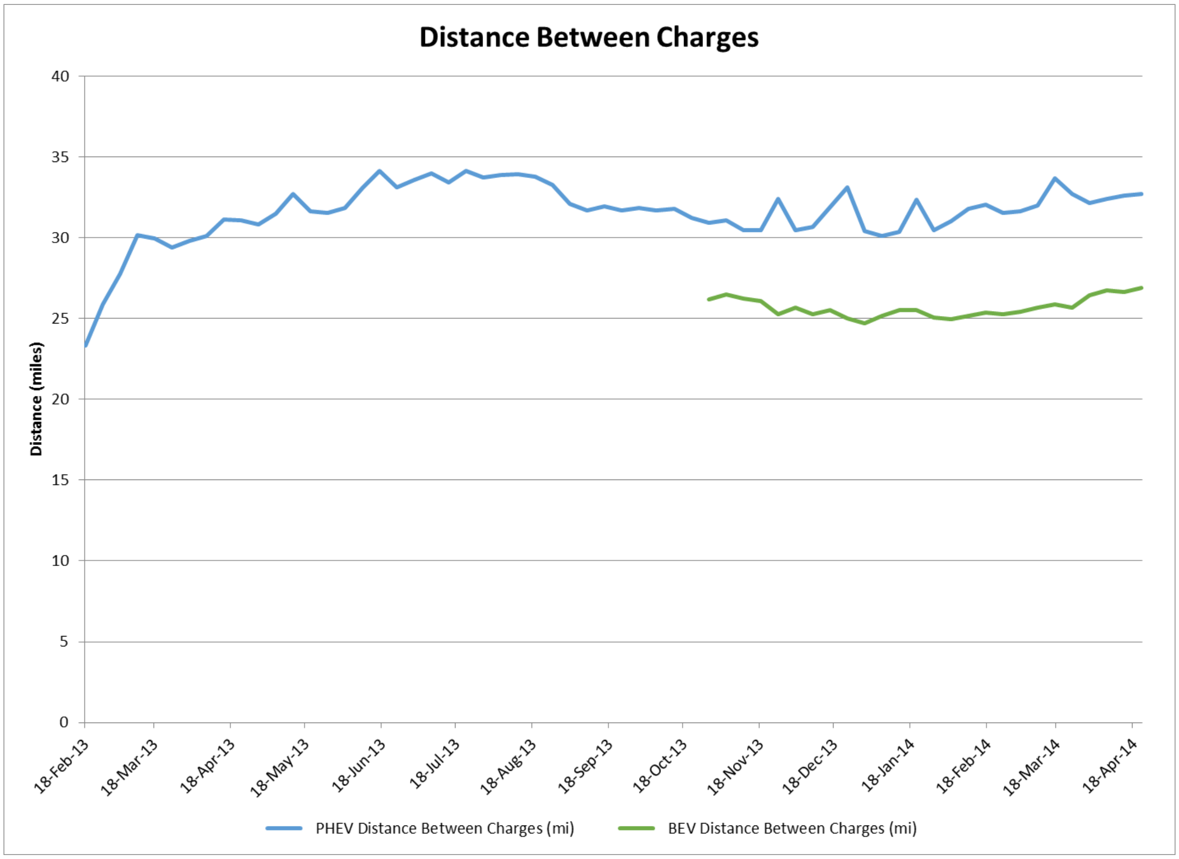

Figure 4 Distance between Charge Events in miles for PHEVs and BEVs

4.2.3 State of Charge at Beginning and End of Charging

It could be seen as an overly conservative habit to recharge the BEV with only approximately 1/3 of the charge depleted, however the level of charge of the battery could be different given the battery performance drivers are experiencing. To better understand this the battery state of charge at beginning and ending of charging should be looked at directly.

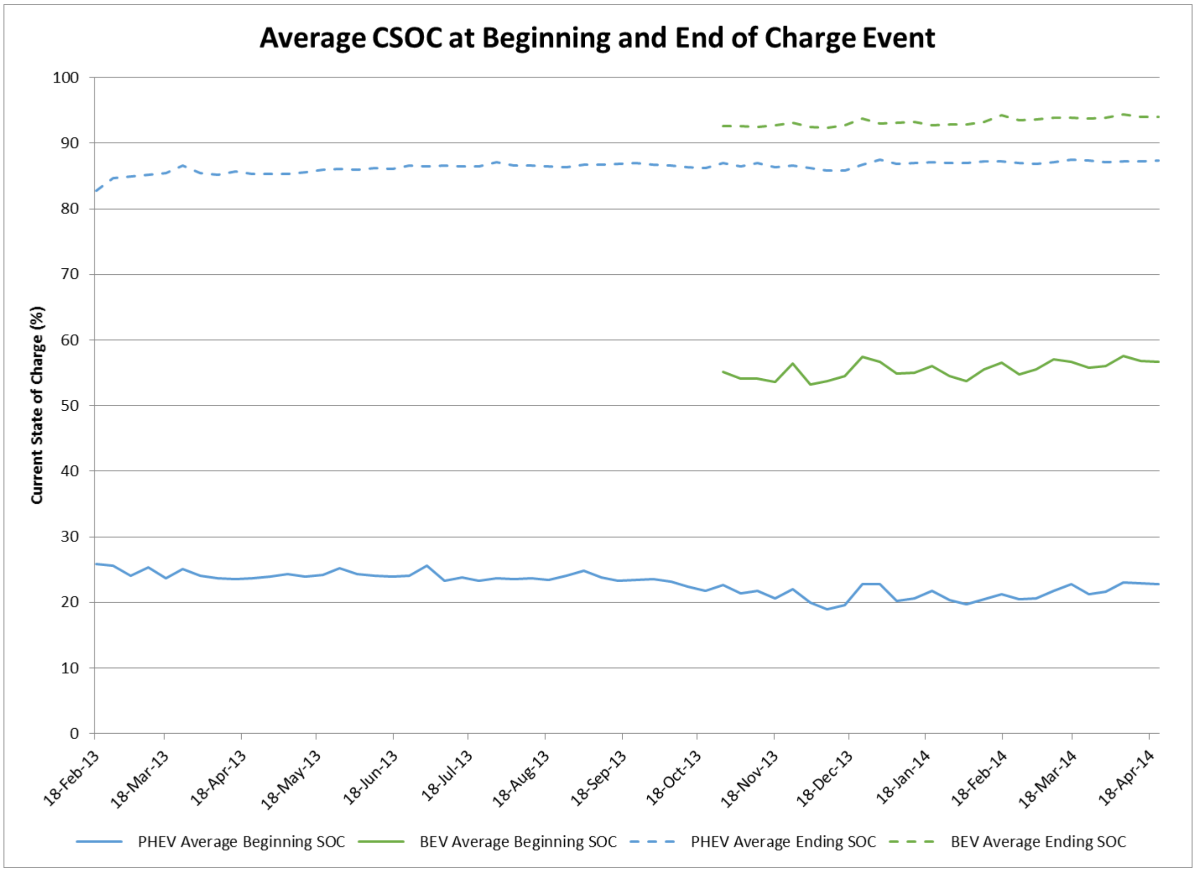

Figure 5 Average CSOC at Beginning and End of Charge Event for PHEVs and BEVs

Figure 5 shows the average beginning and end current state of charge (CSOC) for charge events for both PHEVs and BEVs. On average PHEVs discharge their batteries more fully before beginning to charge, with an average CSOC between 20-25%, whereas BEVs recharge their batteries on average at around 55% CSOC remaining. PHEVs do not recharge their batteries to full as often as BEVs do with an average ending CSOC around 88%, while BEVs recharge to a fairly consistent 92% on average, indicating they more frequently recharge their vehicles to a full 100%.

As with other metrics, there is a slight drop of several percentage points in the charge begin CSOC during the winter months, though the charge end time remains unchanged. Drivers will find that they consume more of their electrical charge during winter months as they experience poorer performance while their driving patterns remain constant or distance decreases. Their CSOC at charge end remains roughly the same, which could mean that drivers experience longer charge events during the winter months. This can be confirmed by analyzing another metric of charge times.

4.2.4 Charger Types: Level 1 and Level 2

Charging time is dependent on the amount of charge that is sent to the battery, the voltage of the electric vehicle supply equipment (EVSE), and the power rating of the onboard charger. Charging time for both PHEVs and BEVs during level 1 and level 2 charging can be found in Figure 6 below.

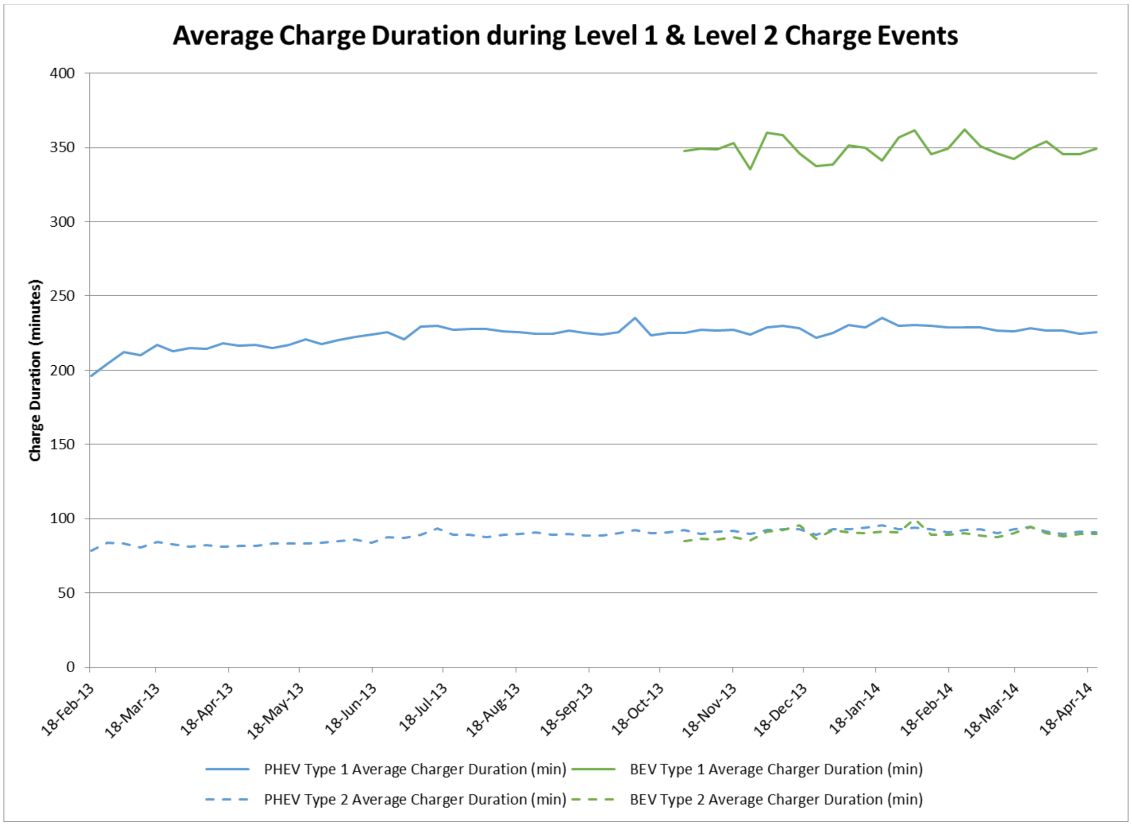

Figure 6 Average Charge Duration during Level 1 and Level 2 Charge Events for PHEVs and BEVs

During level 1 charging, which can be done anywhere with an electrical outlet, the PHEV averages a charging time around 225 minutes, while the BEV requires a significantly longer 350 minutes on average. This is due to the larger size of the battery on a BEV.

Level 2 charging for the PHEV and BEV track similarly with both experiencing average charge times close to 90 minutes. This is a bit surprising due to the competing factors of differing, battery sizes, and average charge depletion between charge events. These factors all attribute differences in how charging should occur, however on average they perform similarly to each other despite these differences.

Though the average durations at level 2 are similar, the percentage of charge events performed at level 2 between the two model types is not. Below in Figure 7 the distribution between each model type and the charger type used in each week is shown.

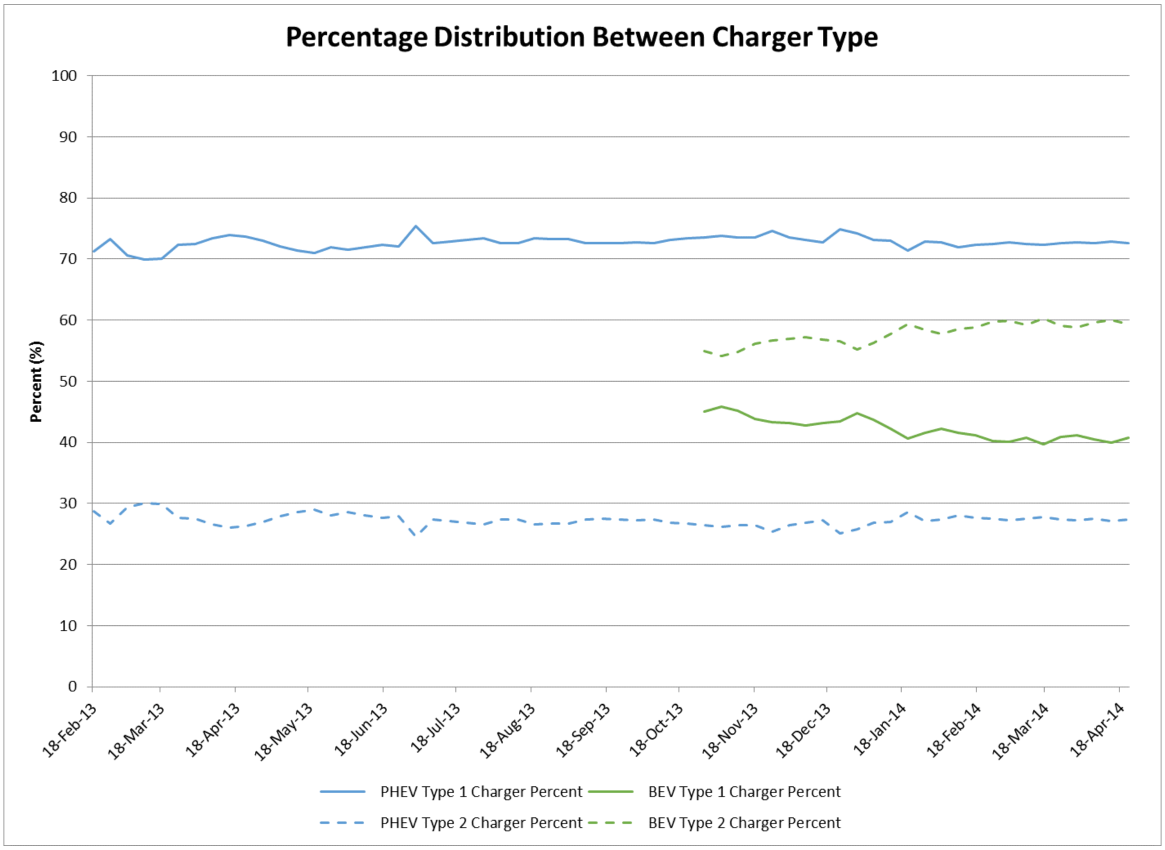

Figure 7 Percent Distribution between Charger Type during Charge Events for PHEVs and BEVs

PHEVs and BEVs vary significantly in their distribution of how often they charge their vehicles at level 1 or level 2. The PHEVs are more apt to charge with a level 1 charger, this means connecting the mobile charger which comes with the vehicle to any 120V outlet they have available. PHEV owners may be more apt to skip purchasing an EVSE and rely solely on level 1 charging, as this data suggests, with slightly over 70% of all charge events for PHEVs being done on level 1.

BEVs in comparison prefer to use a level 2 EVSE to charge their vehicle, with between 55-60% of all charge events being completed on level 2. A BEV driver is much more likely to own a dedicated level 2 EVSE with which to charge, and will generally use level

1 charging for topping off the battery or during situations where they do not have access to a level 2 EVSE.

With charge metrics for both the PHEVs and BEVs analyzed, it is time to analyze the driving metrics recorded.

4.3 Trip Analytics

4.3.1 EV Percent

The comparison of electric miles vs gasoline miles achieved in PHEVs is a very important metric, and one that depends largely on driver behavior. This ratio will be regarded as the EV % whose calculation is shown below:

$$EV\ \%_n = \frac{Electric\ Miles\ Driven_n}{Total\ Miles\ Driven_n} \tag{2}$$

The electric miles driven are specifically the total miles driven by the PHEV with the gasoline engine off in week *n*. In these instances the vehicle would only be propelled by the electric motor. The total miles driven is simply the sum of the trip lengths in week *n*.

Below in Figure 8 is the calculated EV %

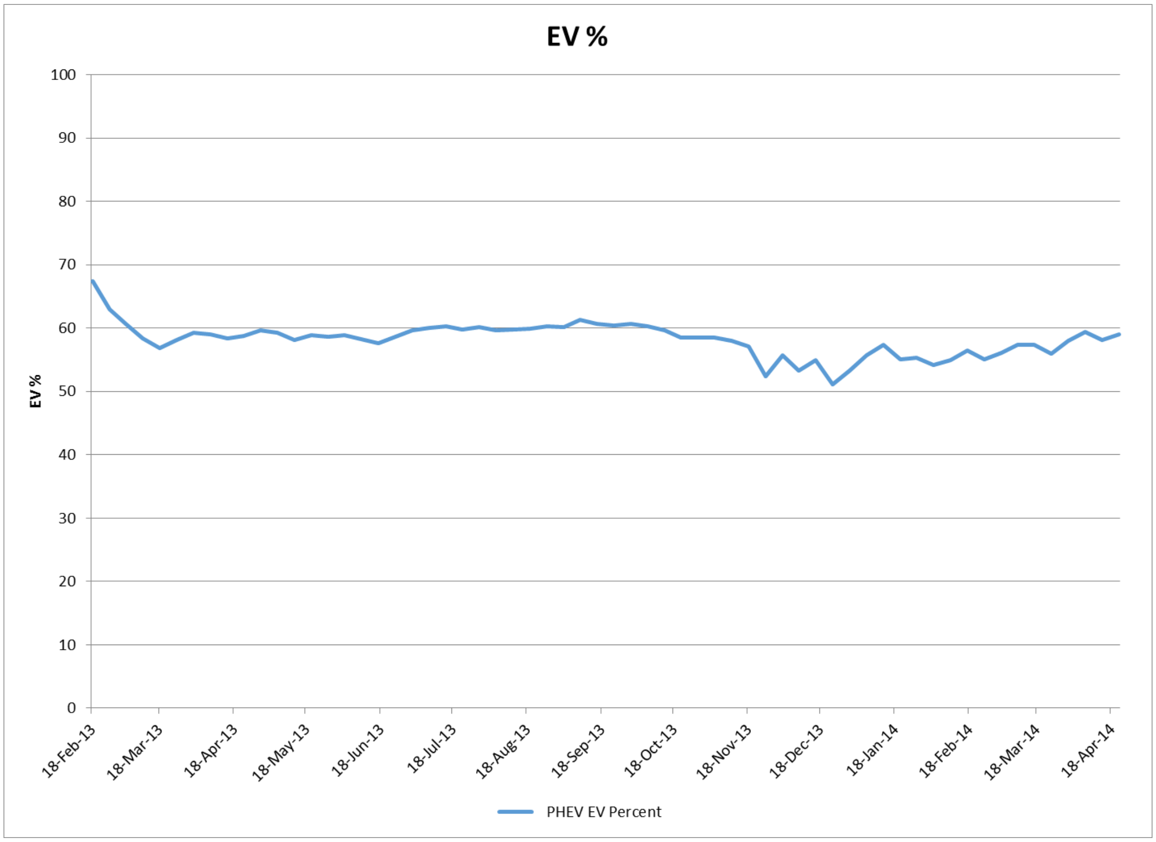

Figure 8 EV % for PHEVs

The EV% yields a value between 45-60% based on the season, where winter performance can dip the electric usage as much as 10%.

4.3.2 Distance Traveled Each Day

The distance driven per day is an important metric to analyze, as it is not intuitive from looking at the distance traveled between charge events, since drivers could charge multiple times per day. However the number of miles driven per day is an important indicator particularly for BEVs, as it is most convenient for BEVs to charge once per day, overnight (Pearre, Kempton et al. 2011). The average and median miles driven per day by day of the week is shown below in Figure 9. This only includes days that vehicles were actually driven. It can be seen that PHEVs on average drive between 42 and 50 miles per day on days that they drive, however the median falls between 25 and 35 miles per day. The average is skewed upwards from the median in particular for PHEVs which have a large standard deviation as seen in Figure 9 due to the days in which PHEVs take exceptionally long trips.

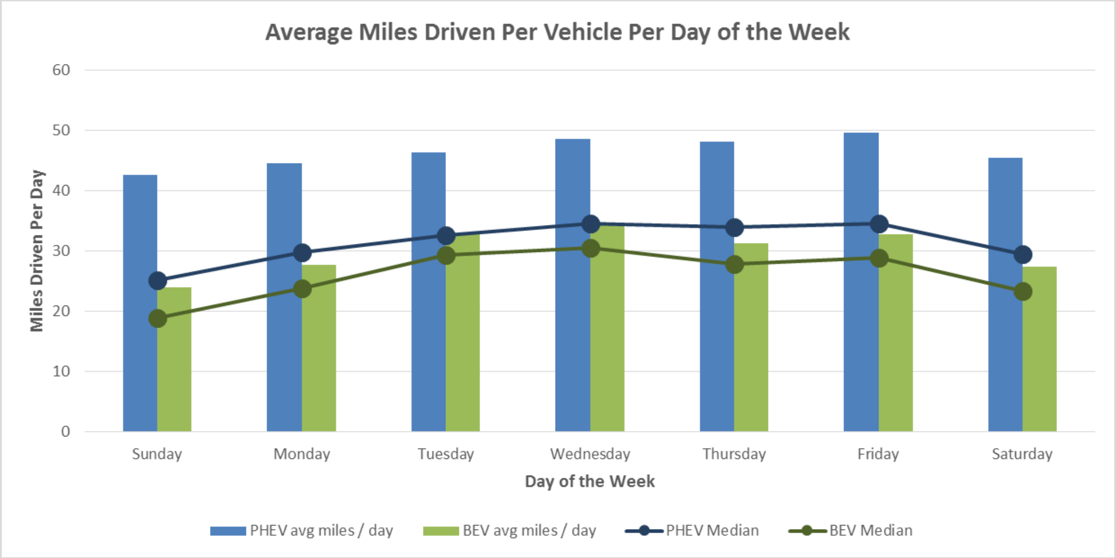

Figure 9 Average & Median Miles Driven Per Day by Day of the Week

BEVs however have a smaller standard deviation as they are less capable of driving long distances in a single day without recharging.

PHEV and BEV trends of driving throughout the week are similar, though more pronounced in BEVs. Both drive the least on Sunday, with Monday and Saturday sharing the spot of the second least driven day of the week. Additionally both drive their maximum distances on Wednesday on average. This is unsurprising as holidays usually fall on the beginning or end of the work week, leaving Wednesday as an unlikely time to be away from work, and therefore not require a commute.

The average miles driven per day across all days driven for PHEVs is 46.58, σ = ± 55.13 with a median of 31.57 miles. The average miles driven per day across all days for BEVs is 30.25, σ = ± 21.37 with a median of 26.16 miles.

Table 1 Miles Driven per Day Statistics

	PHEV					**BEV**				
	Average	**σ**	**Median**	**Days Driven**	**Days Parked**	**Average**	**σ**	**Median**	**Days Driven**	**Days Parked**
Sunday	42.69	58.32	25.23	89.48%	10.52%	23.94	19.35	18.83	85.30%	14.70%
Monday	44.53	54.47	29.83	93.48%	6.52%	27.65	19.27	23.80	92.47%	7.53%
Tuesday	46.33	51.44	32.56	93.80%	6.20%	32.75	21.62	29.33	92.92%	7.08%
Wednesday	48.66	54.17	34.61	93.64%	6.36%	34.39	23.35	30.54	92.27%	7.73%
Thursday	48.18	54.10	33.93	93.06%	6.94%	31.34	21.26	27.78	90.65%	9.35%
Friday	49.57	56.20	34.55	92.88%	7.12%	32.80	22.21	28.89	89.60%	10.40%
Saturday	45.52	57.21	29.45	91.60%	8.40%	27.42	19.82	23.30	90.06%	9.94%

The percentage of days that PHEVs and BEVs did not drive can also be seen in Table 1. A vehicle is considered parked for the day if they did not do any driving on that day. It can be seen that Sunday is the most popular day to not drive the vehicle, and this phenomenon is more pronounced in the BEVs, with a 14.70% chance of not driving compared to a 10.52% chance of remaining parked for PHEVs. Another interesting feature is BEVs have a spike in remaining parked on Fridays compared to PHEVs who only see a slight upward trend. This could be attributed to not having enough remaining charge to complete Friday night outings, which can be done with a PHEV. The BEV is most likely a commuter vehicle, and may not have a sizable range buffer left over before the vehicle is needed again for leisure activities.

A histogram of daily driving by range driven in miles can be seen below in Figure 10. This looks at the percentage of days which were driven for a specific range in miles. This chart only includes days in which the vehicle was driven. Here it can be seen that for both vehicles the majority of trips are short trips, with BEVs filling more of their share in the bottom three bins in comparison to PHEVs. Only 1% of days in which BEVs drive exceed 100 miles whereas 9.5% of days PHEVs drive will exceed 100 miles.

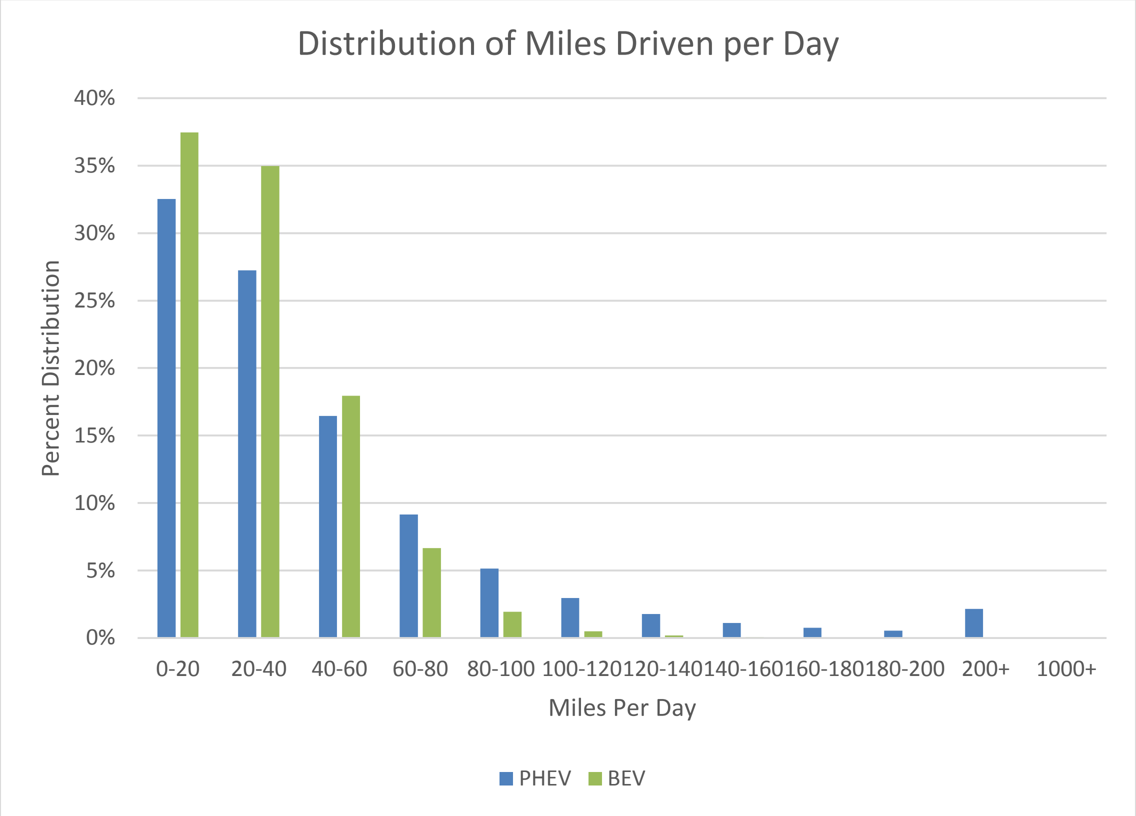

Figure 10 Percent Distribution of Miles Driven per Day

4.4 Fuel Economy

4.4.1 PHEV Fuel Economy

Though this information is not available to us directly, we can look at the gasoline consumed per trip and the trip length to determine the fuel economy of a specific vehicle. The mpg rating of a specific vehicle can be calculated by summing their total miles driven and their total gallons of gasoline consumed to find their average mpg over all of their trips. This can be seen in equation (3) below.

$$vehicle\ mpg = \frac{\sum_{i=1}^{n} Trip\ Length_i}{\sum_{i=1}^{n} gallons\ consumed_i} \tag{3}$$

Here the mpg for the vehicle is calculated by summing all of the trip lengths from trip 1 to trip *n* and summing all of the gallons of gasoline consumed from trip 1 to trip *n*. Dividing the sum of the trip lengths in miles by the sum of all of the gallons of gasoline consumed gives an overall mpg rating for the vehicle. This process is performed for every vehicle in the database. The average mpg rating for the entire fleet is calculated by taking the average of all of the vehicle mpg ratings as seen in equation (4).

$$fleet\ mpg = \frac{\sum_{i=1}^{v} vehicle\ mpg_i}{v} \tag{4}$$

Here the sum of all of the vehicle mpg metrics are taken and divided by the total number of vehicles in the fleet, *v*. The fuel economy results for the fleet of PHEVs are seen below in Figure 11.

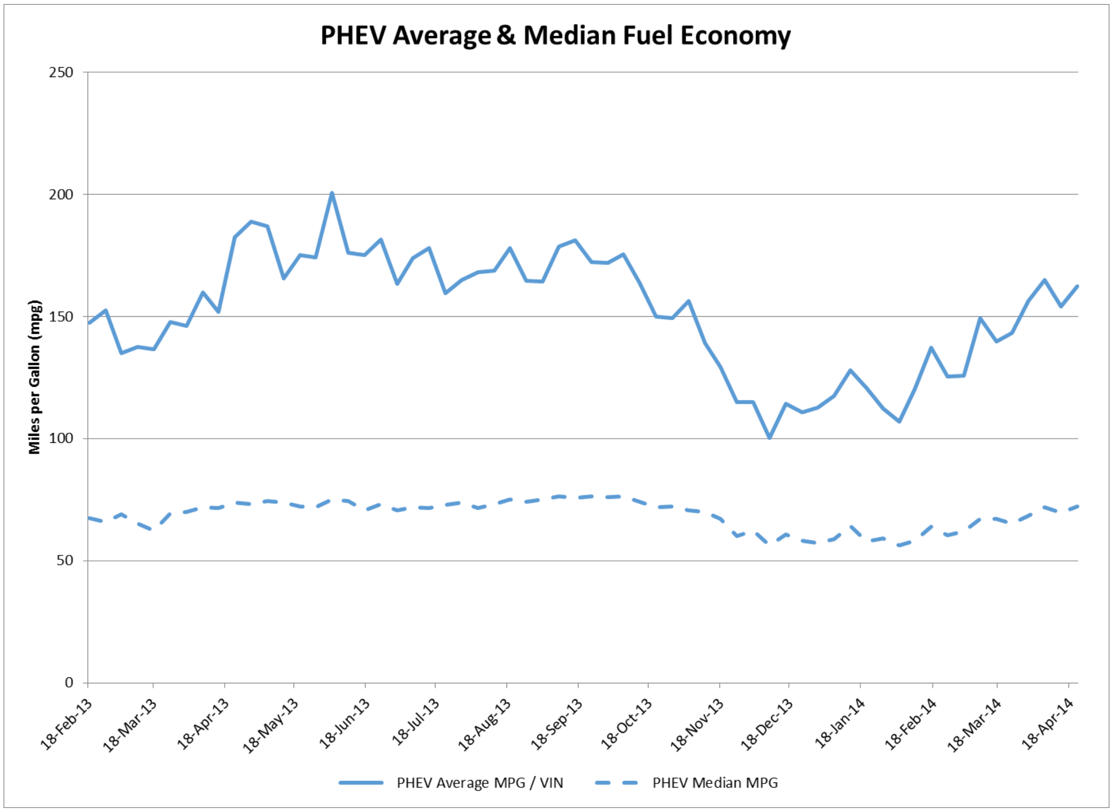

Figure 11 Average and Median fuel economy for PHEVs

Here the average fuel economy can be seen to hover between 150 and 200 mpg during the summer and between 100 and 125 mpg during the winter months. The standard deviation σ is very high for PHEVs, as some vehicles consume very little gas, hovering between 300 and 500 during the summer months with a variation between 200 and 300 during the winter months.

The median provides a more accurate picture of typical PHEV behavior with fuel economy hovering around 70 mpg during the summer and a drop to between 55-60 mpg during the winter months. The winter months are found once again to reduce the efficiency of the vehicle, which can be attributed to the reduced battery performance.

4.5 Geographic Comparison

4.5.1 Time Spent Parked

The data provides a timestamp at key on and key off. This information allows for a calculation of what times vehicles are driving and what times they spend sitting parked. Plotting this information allows patterns in parking behavior to be identified, which also provides insights to how vehicles are being used. These plots were generated on a weekday vs weekend basis to understand how trip behavior changes for days where commuting is expected as well as days reserved for more leisure activities and errands. It was expected that we would find vehicles parking for long periods in the early morning as they arrived at work, as well as vehicles parked at night for extended periods of time. It was decided that this analysis would be completed over several major cities in order to understand how parking behavior changed with different metropolitan areas, if it all. The cities selected were Atlanta, Los Angeles, and New York.

Analysis of weekday parking was expected to show workplace parking during the middle of the day. Below in Figure 12 is a chart showing the duration a vehicle in Atlanta was parked during a weekday on the y axis, with the hour of the beginning of the parking event shown in the x axis.

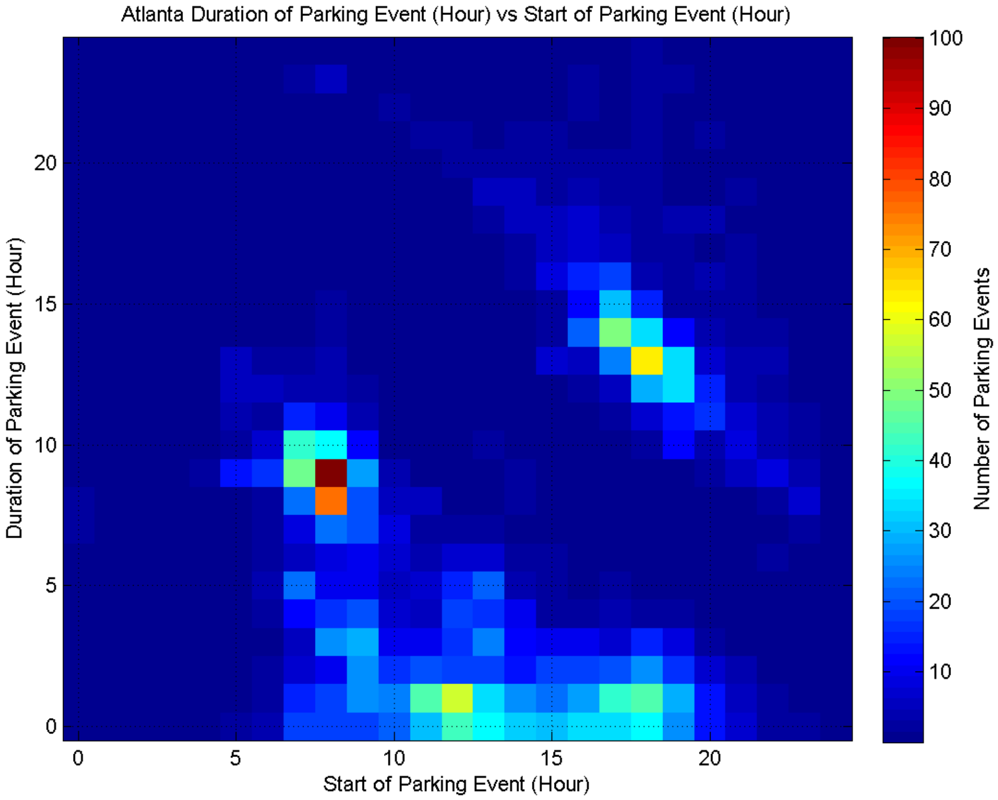

Figure 12 Duration of Parking Events on Weekdays in Atlanta

This figure reveals several areas of concentrated parking events. First there is the most concentrated area of starting a parking event within the 8am hour, and remaining parked for nine hours, the eight hour duration is also heavily concentrated. This is the commuters that were expected to be found in this analysis, as they remain parked for the entire work day.

The second concentrated area appears between 11am and 1pm, with durations of less than an hour and an hour to two hours, with the highest concentration being at noon lasting between one and two hours. These are obviously people headed out to lunch or other midday errands. An in depth analysis of particular vehicles would be required in order to understand what percentage of these people are the same commuters who travel to work at 8am, although the slightly highlighted area at 8am with a duration of three hours is likely to be these same people, representing a smaller portion of events then those found at midday. These short duration trips continue through until approximately 6pm.

The third concentrated area is the band surrounding those who park their vehicles at 5 or 6pm and remain parked for thirteen to fourteen hours. These are people who have returned home for the day and do not break their parking event until the next day. The parking event which occurs most likely at the driver's home can be seen as a wide band starting around noon and ending around 11pm with an equally wide duration between eight and twenty hours. This shows that during the weekday, though the largest concentration of drivers return home at 5 or 6pm, representing commuters who do not drive their vehicles again until the following morning, there are also individuals who return home at a wide range of hours.

Looking at this same heat map representation of parking for Los Angeles and New York reveals the same three major regions of parking, but with slight differences in their concentrations. Below in Figure 13 is the same heat map of parking events found on weekdays in Los Angeles.

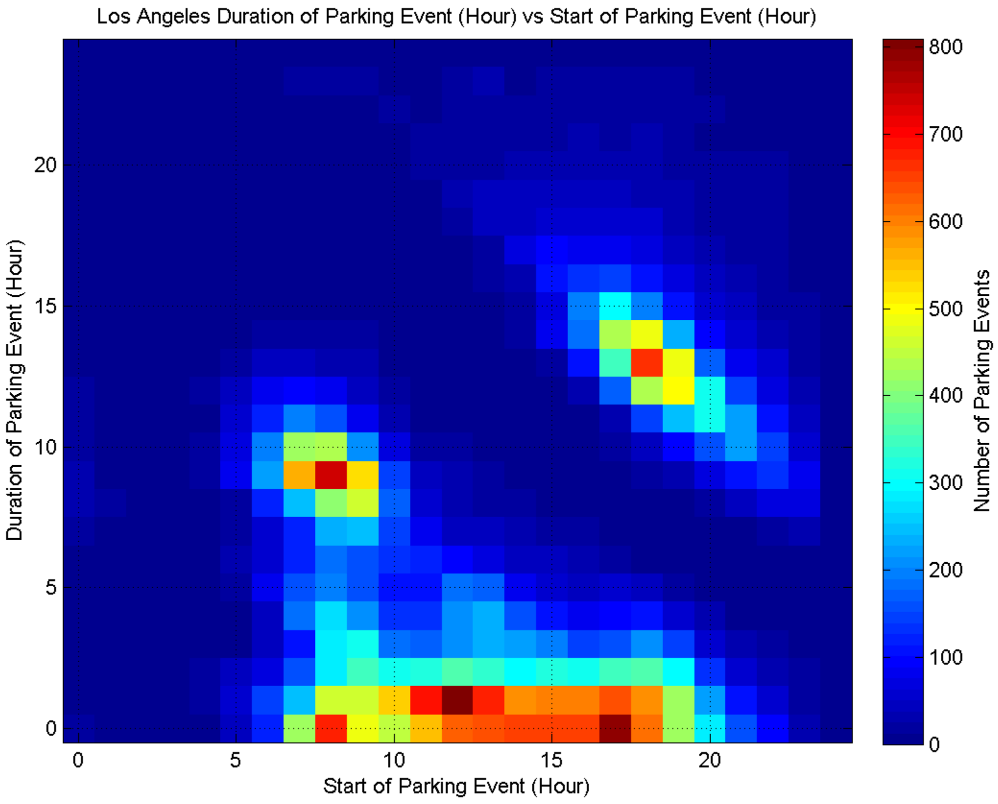

Figure 13 Duration of Parking Events on Weekdays in Los Angeles

Los Angeles differs slightly from Atlanta in that the time at which commuters begin work is slightly more variant, though beginning the parking event at 8am is still most common. There is also a concentrated area at 8am of events which take less than an hour that was not found in Atlanta. This could be commuters stopping consistently on an errand before arriving at work, for example to purchase breakfast or coffee. Additionally Los Angeles has more short duration parking events throughout the entire day, rather than the concentrated midday lunch hour concentration found in Atlanta. It could be that Los Angeles electrified vehicles see much more use as errand runners throughout the weekday as opposed to strictly commuter vehicles, which is more pronounced in Atlanta.

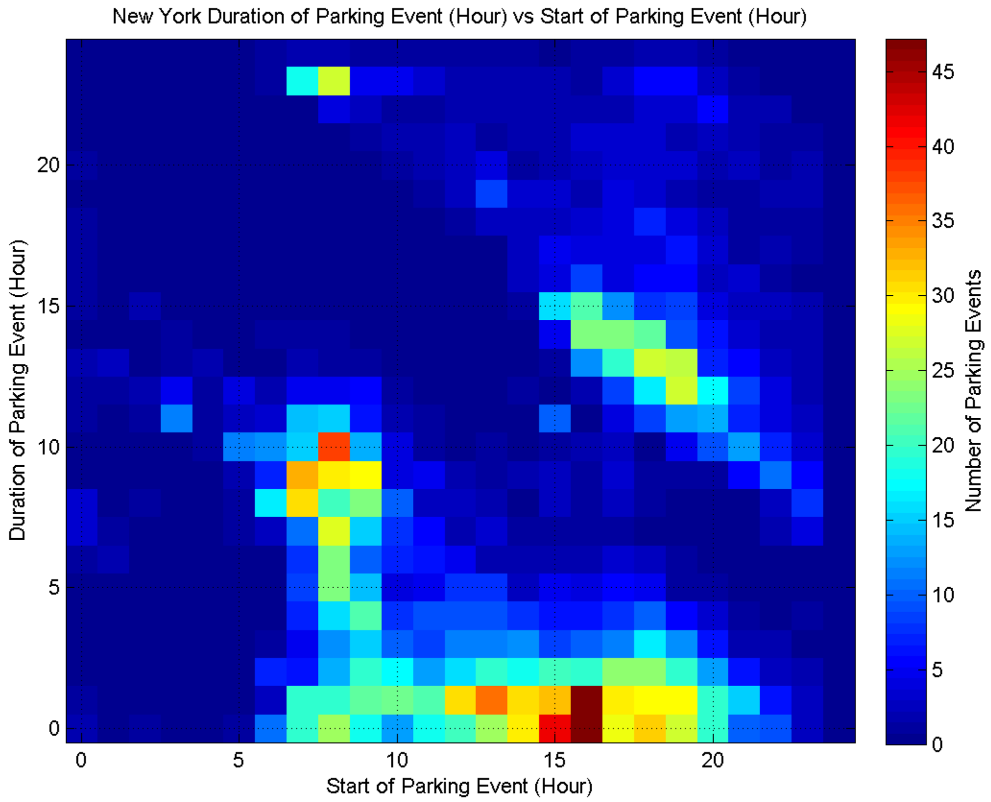

Figure 14 Duration of Parking Events on Weekdays in New York City

New York City displays a unique event at 8am in which a large band of durations from less than an hour through to ten or eleven hours. This appears less discrete than both Los Angeles and Atlanta. New Yorkers also are most likely to go out and park their cars at 4pm for a short duration rather than the more popular midday short duration parking events found in Los Angeles and Atlanta. There is also a small but significant group of drivers who park their vehicles at 8am but leave them parked for nearly an entire day. These could be fleet vehicles which drivers are allowed to take home with them, but may not be their main form of transportation. New York City has a less structured commuter group than the previous two cities which is not surprising, as it also has the most robust mass transit system, so a personal vehicle has a smaller chance of being a commuter vehicle.

These differences in the use of electrified vehicles throughout the weekdays reveals that though all regions have some commuter group, they differ in the percentage of use as a whole. The times with which vehicles are most active is also differing between the three regions with the concentration of short duration trips revealing very different driving behavior of electrified vehicles.

These differences in weekday behavior are vital for the interested parties of electrified vehicles to understand, in order to better optimize vehicle design and charging infrastructure. Atlanta is clearly the most commuter based city of the three, and would benefit most from larger batteries with longer range in order to drive from the suburbs to the workplace on electricity, as well as workplace charging which could help boost electrified driving. Additionally the midday concentration of short parking events in Atlanta show that restaurants close to commercial zoned areas who cater to workplace meals may find a greater benefit in offering charging infrastructure than perhaps New York City. Los Angeles would require a smaller battery sized vehicle than Atlanta as the majority of parking events are short and not as commuter focused. A short range PHEV with extensive charging infrastructure in retail and restaurant locations could be an optimal electrified solution for Los Angeles. Lastly New York may require charging infrastructure at these 4pm short duration locations, but workplace charging may see less of a benefit with the wide band of durations found at 8am. These locations with additional charging infrastructure should also be inspected for adequate grid support, as localized charging can have adverse effects on electrical grid equipment, shortening its lifespan if overloaded (ECOtality 2013).

The time spent parked was also analyzed for weekends for these same three metropolitan areas. It was expected that there would be little to no commuting concentrations of vehicles parked but more short duration trips throughout the day for errands. Figure 15 below features the time spent parked during the weekend in Atlanta.

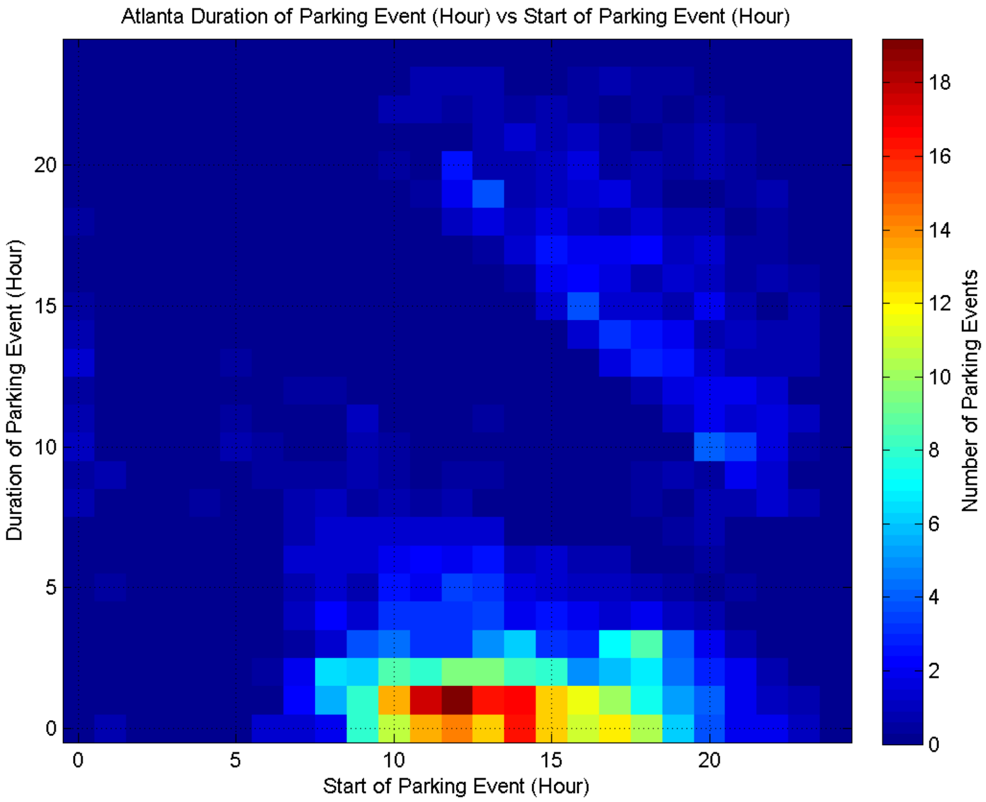

Figure 15 Duration of Parking Events on Weekends in Atlanta

This driving and parking behavior for Atlanta is what would be expected, many short duration parking events throughout the day. The duration of these midday events in Atlanta are slightly longer than what is found during the weekdays, as drivers stop to park at locations for upwards of three hours. Parking events begin later in the day compared to weekdays as well.

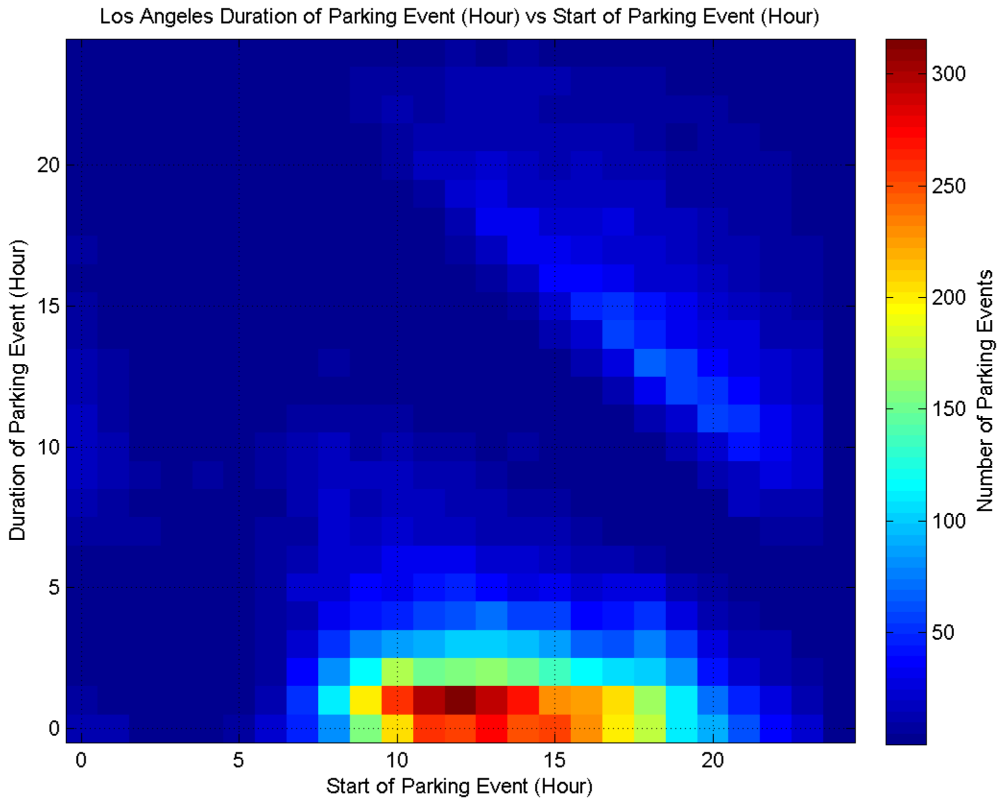

Figure 16 Duration of Parking Events on Weekends in Los Angeles

Los Angeles parking events look very similar to those found in Atlanta, though the duration of parking events on the weekends is minimally longer than those found throughout the week. Revealing that parking events in Los Angeles vary less between weekday and weekend than in Atlanta, where commuting is the dominant source of parking events throughout the week.

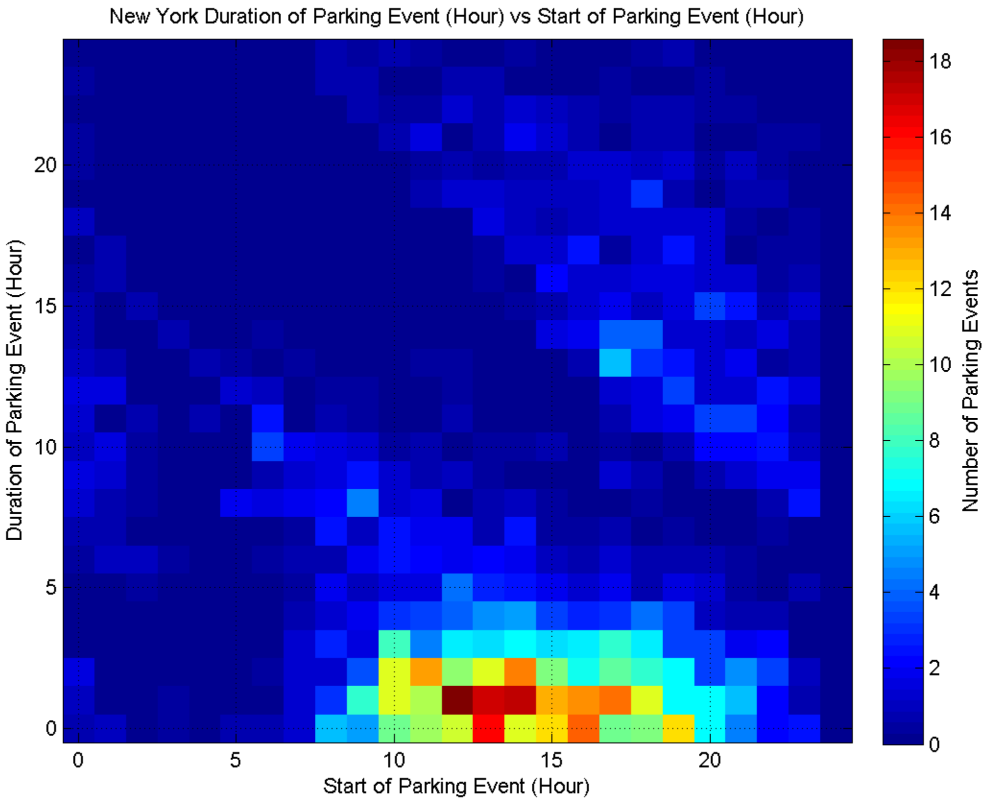

Figure 17 Duration of Parking Events on Weekends in New York City

New York City shares many commonalities with Atlanta and Los Angeles on the weekends except for the fact that parking events are more concentrated in the middle of the day with less spread than the other two cities.

Overall there is less variance in weekend parking events across the three cities than can be found during weekday vehicle use. It could be argued that it is more important to analyze weekday charging and driving behavior when considering regional differences of electrified vehicles, as their weekend behavior is largely similar. Charging infrastructure is obviously only of use in locations where vehicles remain parked, preferably between 1-4 hours to acquire a substantial charge, and when considering locations for infrastructure both weekend and weekday behavior should be investigated to understand the full picture of how vehicles in the local area are being utilized. In addition, if an electrified vehicle is to be marketed as a weekend errand runner with a short electrified range, it should fare well in a wide range of metropolitan areas, however for weekday driving and commuting, the behavior of the local residents needs to come into consideration as they differ significantly from region to region.

4.5.2 Arizona vs. Oregon – Trip and Charge Information

In order to understand additional regional differences in the data, the states of Oregon and Arizona were compared. This data includes all electrified vehicles of both PHEVs and BEVs operating within the two states. Below in Table 2 are many of the metrics comparing the performance of the PHEVs in Arizona and Oregon.

Table 2 Arizona vs. Oregon Performance by PHEVs in Winter

	Week 45		Week 46		Week 47		Week 48		Week 49	
	16-Dec		23-Dec		30-Dec		6-Jan		13-Jan	
	AZ	OR	AZ	OR	AZ	OR	AZ	OR	AZ	OR
Charges Per Vehicle	8.03	9.37	7.53	7.15	7.64	7.90	9.15	9.04	9.14	9.43
EV Percent	69.51	64.08	65.50	61.40	67.30	63.49	69.63	66.83	69.40	64.86
Average Trip Length (mi)	8.86	8.67	9.77	9.39	9.35	8.96	8.80	8.28	8.83	8.77
Trips Between Charges	4.19	3.44	4.18	3.56	3.98	3.44	3.85	3.32	3.98	3.29
Distance Between Charges (mi)	38.37	30.24	42.80	34.22	38.31	31.31	34.55	27.69	35.97	29.12
Average Beginning SOC	24.43	21.92	27.92	25.93	27.46	27.81	23.68	22.32	25.70	22.24
Average Ending SOC	86.66	86.21	85.51	88.58	86.32	89.90	82.95	86.25	85.35	85.44
Average Charge Duration (min)	174.38	178.27	166.77	179.57	182.24	186.56	162.70	180.85	172.45	181.75
Type 1 Charger Percent	69.47	69.04	69.77	76.30	71.59	77.84	66.74	73.27	64.29	73.64
Type 2 Charger Percent	30.53	30.96	30.23	23.70	28.41	22.16	33.26	26.73	35.71	26.36
Average MPG / VIN	184.41	146.27	158.70	119.06	162.88	119.54	167.79	155.20	205.13	138.71
Median MPG	80.89	64.30	65.38	58.65	70.89	67.82	82.60	87.53	83.95	68.19

A subsection of the performance of PHEVs in Arizona and Oregon during winter was taken over five weeks. The data begins with the week of December 16th 2014 and ends with the week of January 13th 2014. First we can see that Arizona PHEVs travel 5-10 miles further between charge events than Oregon PHEVs. However, Arizona PHEVs also have an EV percent about 5% higher than those found in Oregon. The fact that Oregon PHEVs drive shorter distances between charges as well as achieving less electric driving indicates the battery may be underperforming due to winter temperatures which are lower throughout Oregon. This is reinforced by the fact that Arizona drivers are charging less often or equally to Oregon drivers. Additionally, Arizona drivers take more trips between charge events with equivalent average trip lengths, further identifying weather as an impacting variable. The driving and charging behavior found in Oregon of slightly shorter trips and more charge events per week would generally lead to an increased EV%, but this is not the case found here.

This reduced battery performance is most likely hindering Oregon's fuel economy ratings as well, with average and median MPG metrics lagging behind Arizona. However the fuel economy ratings achieved by PHEVs are also heavily dependent on driving style, which is unknown with this data set. It could be that Oregon drivers experience heavier traffic on average, or have a more aggressive driving style, which would impact the fuel economy achieved.

Arizona PHEVs also utilize slightly more level 2 charging than Oregon PHEVs. Since PHEVs perform the majority of their charging at home it could be inferred that more Arizona drivers opt to install level 2 charging stations at their home than drivers in Oregon. A more in depth look of the public charging infrastructure available between these two states could provide revealing background to the effects it has on home charging solutions.

The same analysis for BEVs in Arizona and Oregon can be seen below in Table 3.

Table 3 Arizona vs. Oregon Performance by BEVs in Winter

	Week 45		Week 46		Week 47		Week 48		Week 49	
	16-Dec		23-Dec		30-Dec		6-Jan		13-Jan	
	AZ	**OR**	**AZ**	**OR**	**AZ**	**OR**	**AZ**	**OR**	**AZ**	**OR**
Charges Per Vehicle	6.76	8.23	4.58	6.90	5.46	7.43	6.83	8.14	7.55	7.68
Average Trip Length (mi)	8.19	7.13	7.85	6.96	8.11	7.12	8.38	7.13	8.27	7.43
Trips Between Charges	3.43	3.14	3.51	3.12	3.42	3.13	3.44	3.17	3.40	3.20
Distance Between Charges (mi)	27.76	21.59	27.51	20.95	27.36	21.50	28.38	21.83	27.69	22.87
Average Beginning SOC	53.41	55.46	56.12	58.24	54.50	57.35	49.04	54.17	55.17	53.46
Average Ending SOC	93.33	92.75	95.82	94.99	95.57	93.62	93.89	91.36	94.78	93.89
Average Charge Duration (min)	226.65	232.30	220.93	239.46	222.78	234.84	212.95	237.58	188.44	262.46
Type 1 Charger Percent	42.00	55.25	42.25	53.00	39.79	55.96	41.06	58.66	36.75	55.62
Type 2 Charger Percent	58.00	44.75	57.75	47.00	60.21	44.04	58.94	41.34	63.25	44.38

Distance between charges follows the same pattern seen in PHEVs, with Arizona drivers traveling further between charge events than Oregon drivers. Oregon BEVs charge more often than Arizona BEVs, about one to two more times per week. This is more overstated than the difference that was seen between the PHEVs in the two states. BEVS are more apt to use public charging options than PHEVs, so it could be that Oregon has more public charging available than Arizona.

Arizona BEVs have slightly longer trip lengths than BEVs in Oregon and take an additional half trip between charges on average over Oregon BEVs. There is also a difference seen between the types of charging the BEVs utilize, similar to the difference seen in PHEVs, with Oregon vehicles opting for more level 1 charging than Arizona vehicles. Arizona BEVs utilize level 2 charging slightly more than half of the time while Oregon BEVs utilize level 2 charging slightly under half of the time. It’s difficult to say what causes Oregon electrified vehicles to gravitate towards more low voltage charging than Arizona vehicles. Arizona drivers could experience more range anxiety than Oregon drivers, which influences them to revert to level 2 charging whenever they get the chance in order to minimize the time spent charging. A more in depth analysis on the preferred charging type between these two states, and perhaps analysis of other states could better reveal the justifications of this behavior.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

The metrics analyzed in this study have covered a wide range of electrified vehicle charging and driving behavior on a large scale. This includes trip and charge event analytics, fuel economy as well as comparison between performance in different geographic metropolitan areas and states. This chapter will summarize the thesis and discuss what has been investigated, as well as provide examples of future work which could be performed in the field of electrified vehicle charging and driving patterns. Overarching conclusions will be drawn on the importance of various charging and driving behavioral metrics.

5.1 Thesis Summary

This thesis sought to investigate the charging and driving patterns of thousands of PHEVs and BEVs from both industry and public sources, with the hopes to analyze proven metrics as well as establish new metrics for future electrified vehicle benchmarking and analysis.

Chapter 2 considered the literature performed by others on electrified vehicles and their charging and driving behavior. The most significant of these studies being the EV Project from INL and ECOtality.

Previous studies on range anxiety were also investigated as that would be a consideration in some of the metrics of this study, particularly how it changes over time. The potential environmental benefits were also investigated in order to put the performance of this study’s vehicles into context. Lastly studies on electrified vehicle economics and psychology were investigated to better understand who is buying electrified vehicles, in order to provide background to who the most likely drivers are in this project.

Chapter 3 discussed the methodology of this study, how the vehicle data was received, analyzed, and processed.

Chapter 4 discussed the analytics and metrics derived from the data. First the charge analytics were analyzed, these consisted of the number of charge events performed per week, the number of trips and distance in miles traveled between charge events, the average state of charge at the beginning and end of charge events as well as the preferred charger types used. It was found that PHEVs charge slightly more often than BEVs and that holidays can be seen to influence the number of charge events performed, with drivers not charging their vehicles as often when they have time off for holidays. The number of trips taken between charge events was similar between PHEVs and BEVs, however PHEVs travel between 5-10 miles further between charge events than BEVs on average. BEVs recharge their vehicles at a higher state of charge than PHEVs, usually choosing to charge the battery at levels slightly above 50%, compared to PHEVs who charge around 20%. Both charge their vehicles up to nearly a full battery on average. BEVs utilize more level 2 charging than PHEVs with a distribution of about 55% level 2 and 45% level 1 for BEVs, compared to PHEVs which utilize about 30% level 2 and 70% level 1 charging.

The trip analytics were then analyzed which covered the EV% of PHEVs, which is the percentage of miles driven electric in comparison to the total number of miles driven. PHEVs average 50%-60% of miles driven are electric. The distance traveled on each day was examined revealing that BEVs drive less than PHEVs on any given day, and that weekdays see more driving per day on average than weekends.

Fuel economy metrics of the PHEVs were analyzed. The PHEV average fuel economy varies considerably depending on the season but median fuel economy hovers between 70 and 55 mpg for summer and winter respectively.

Geographic comparisons were then drawn between select metropolitan areas and states. First the time the vehicles spend parked was examined, for Atlanta, New York City, and Los Angeles. Finding out when vehicles remain parked is important to local municipalities who want to install charging infrastructure effectively. It is also important to understand which electrified products would do best in different regions, areas where drivers remain parked for short periods of time, such as Los Angeles, may benefit more from a combination of a smaller battery and a robust charging infrastructure. It was found that weekend parking events look fairly similar between the three metropolitan areas but weekday parking events vary considerably, with Atlanta being the most commuter focused and Los Angeles having more retail trips throughout the day.

An analysis of the charge and trip metrics discussed earlier was run on two separate geographic regions, Arizona and Oregon, to better understand the differences in their vehicle performance during winter, as well as other differences not tied to temperature. It was found that Arizona drivers travel further between charges and charge less often, but still average a higher EV% than Oregon drivers. Additionally, Oregon drivers prefer level 1 charging over level 2 compared to Arizona for both PHEVs and BEVs, which could be caused by differences in public charging availability or differing levels of range anxiety.

5.2 Discussion and Conclusions

This study has examined many aspects of charging and driving behavior on a large scale, which helps reinforce previous work done by similarly large studies such as the EV Project by Idaho National Labs. It is the goal of this study to supply a base of understanding in electrified vehicle charging and driving behavior, so future studies may have a foundation of fleet data from which to base their own studies.

The average trip length of PHEVs is slightly longer than BEVs, which has been predicted by other studies. This is most likely due to the long trips that exceed the BEVs range, which PHEVs are capable of making on gasoline. The average distance per day of BEVs is less than PHEVs. This means either the battery size of the BEVs are limiting their driving patterns, due to the reduced range in comparison to a PHEV, or the driving styles of BEV drivers are generally shorter distance than those of PHEVs.

It would make more sense that those who know they drive shorter distances per day would purchase a BEV over a PHEV, and that the range of the BEV is not in fact limiting their driving patterns. Though if the average PHEV is traveling 30-50 miles per day compared to a BEVs 20-30, it could be that an additional range buffer is required before PHEV drivers would consider a BEV for their daily needs.

When looking at the distance traveled between charge events, vehicles are fairly similar with BEVs around 25 miles between charge events and PHEVs at 30-35 miles. These results could be from the fact that BEVs generally charge less than PHEVs and at night while they are home. However PHEVs are apt to charge more often to minimize the amount of gasoline they consume. This study looked at electrified vehicles from North

America as a whole, and though the majority were from regions which support large public charging infrastructure, such as California, New England, and the Pacific Northwest, there was still a sizable portion of vehicles hailing from other parts of North America which may not have robust public charging available. This would increase the distance traveled between charge events.

Given the fact that some trips exceed hundreds of miles, achieving 100% electric driving with a PHEV would be difficult to attain across an entire fleet, who likely bought the vehicle partly for the convenience of not being constrained by the battery range. Future studies could assist in understanding how different PHEV electrified ranges impact the quantity of trips done electrically.

The geographic comparisons of parking information yielded that weekday driving can differ significantly between metropolitan areas. However weekend driving is more uniform across regional areas. It appears that cities which are built out such as Atlanta require larger battery range in order to satisfy longer commutes, compared to cities which are built up such as New York City require smaller battery ranges, as commuting does not appear to be the vehicle's primary use.

Additionally charging infrastructure should be investigated on a per case basis depending on the city, as driving patterns differ widely between them. In this way, national policies regarding public charging infrastructure placement may be a less effective use of resources compared to tailored solutions for individual metropolitan areas. Though commuting was not found to be the primary use of the vehicle in Los Angeles and New York City, it was still present, showing that workplace charging could be a top priority for charging infrastructure. This essentially doubles a full electric vehicle’s usable range from home during the weekday, as the driver’s home is not the only charging location. Workplace charging could have major effects on electrified vehicle adoption rates, as well as expanding the distance from the city center which makes an electrified vehicle a feasible purchasing decision. PHEVs could see additional cost savings and improvements in electrified miles driven with workplace charging, which in turn leads to environmental benefits.

Other areas which saw large quantities of parking events were short parking events throughout the day on the weekend. All weekend parking profiles between the three cities showed substantial parking events between 1-3 hours. This errand running or leisure time spent parked could have the potential to operate as a charging location. Areas where electrified vehicle drivers spend their weekends could make prime charging locations. It should also be noted that 1-3 hours at these locations on a level 2 charger could potentially fully recharge the battery, so level 3 charging should be looked at a case by case basis for these locations based on parking behavior and the prevalence of future vehicles to provide level 3 charging.

In conclusion this study helps to lay the ground work for a new and exciting field of research on electrified driving and charging behavior, adding data and metrics from thousands of PHEVs and BEVs which can support future studies.

5.3 Future Work

The data set used to create this thesis allows for many additional aspects of driving and charging behavior to be investigated. With additional time the current dataset has the potential for the investigation of the following driving and charging metrics.

5.3.1 Geographic Studies

More geographic comparisons could be drawn with more time. Additional state and metropolitan areas could be investigated with a case by case study. Different parameters could be considered on a geographic basis, such as average trip length, or distance traveled in a single day. This would paint a more descriptive picture of how drivers are performing in different regions and to what degree geography affects these parameters. It is already known that geography can have significant effects on fuel economy in conventional vehicles, however this effect may be more pronounced in electrified vehicles.

5.3.2 Effects of Charging Infrastructure

Regions with a higher density of available public charging stations will likely exhibit more electrified driving in PHEVs and reduced range anxiety in BEVs. These relationships could be investigated more in depth by cross referencing the results from this study of particular regions with a database of available public charging locations in order to find correlations between charging and driving metrics and charging infrastructure density. Additionally, the prevalence of lack of workplace charging could be compared to various regions from this study to understand the contributions workplace charging makes in electrified charging and driving behavior.

Future studies could investigate whether trends seen by this study and other large telematics based studies are definitive across a broad range of electrified vehicle driving and charging parameters. Any aspect of this study could be examined in more detail to better understand why electrified vehicles are performing in the manner in which they do. Hopefully future researchers will utilize the findings of this study to confirm future electrified vehicle behavior trends, and encourage more in depth investigations of these metrics. Electrified vehicles are a relatively new market and how drivers utilize these vehicles is not yet fully understood. Charging and the effects of a limited range which cannot be readily restored requires drivers to take on new driving habits not seen in conventional vehicles. PHEVs are providing economic incentive for drivers to maximize their electric miles and reduce their gasoline consumption, which results in behaviors unique to electrified drivers. Future studies will be able to add a better understanding of the charging and driving behavior of electrified vehicles.

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